

Name of class:-

Semiconductor physics & Devices

EC 310

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28/2/2017

- Text :- Different Books

- Grading system :-

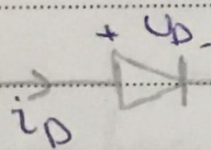
2 mid terms 40% \rightarrow 50%

one final 45% \rightarrow 60%

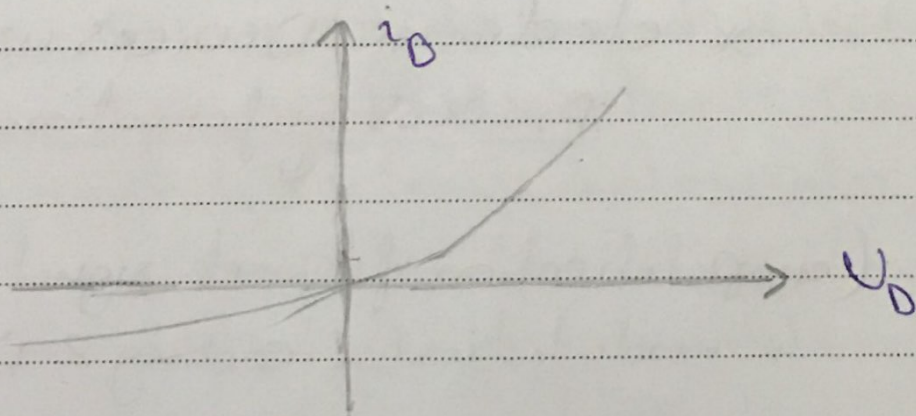
Hws 5% \rightarrow 10%

- Topics to be covered :-

- 1 - semiconductor materials.
- 2 - current flow in semiconductors.
- 3 - pn junction (Diode).



$$i_D = I_S (e^{\frac{V_D}{V_T}} - 1)$$



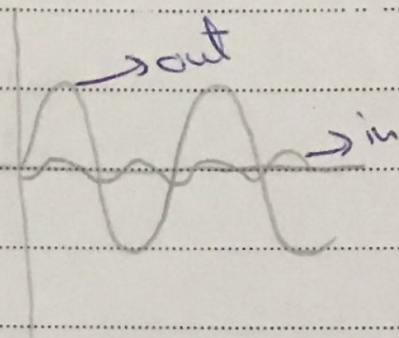
4- Diode circuits.

5- Bipolar Junction transistor (BJT).

6- field effect transistor (FET).

Amplify here

$$A_v = \frac{V_o}{V_{in}}$$



* the names of the course:-

- Introduction to semi(conductors physics & Devices)
- solid state electronics

* electronic Devices used to ~~process~~
process information

(amplification of weak signals + filtering
+ modulation + coding & Decoding)
تقنية / تغيير

* Moore's law: device density on chip every two years.

- featured size (14 nm)

* Brief History:-

1st half of 20th century (1900-1950)

Dominated by vacuum tubes.

- 1904: Fleming invented the valve

(vacuum tube diode)

- 1906: DeForest's oscillators & multivibrators

were designed using Diodes &

Triodes

- 1920: First radio station was created.

- 1930: B & W TV introduction.

- 1940: Radar was developed.

- 1946: First electronic computer called electronic Integrator & computer (ENIAC).

2nd half of 20 century (1950 \rightarrow ...)

* Dominated by solid state electronic devices.

* Semiconductor:-

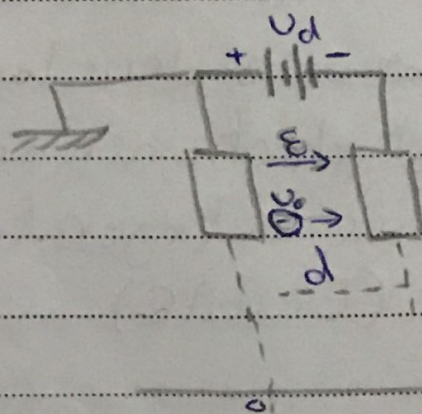
controlled flow of charges is fundamental to the operation of electronic devices.

\Rightarrow materials used must provide:-

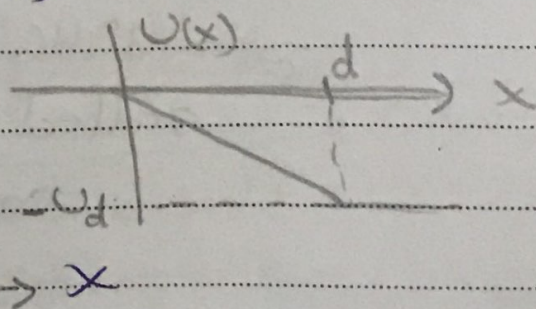
mobile charges.

process that governing the flow of mobile charges.

* The potential energy barrier:-



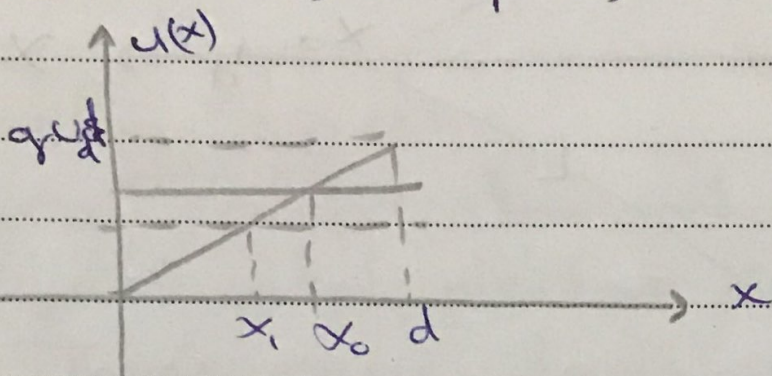
$\Rightarrow V(x)$ is linear function



المجال الكهربائي

- corresponding potential energy $u(x)$

$$u(x) = -qU(x)$$



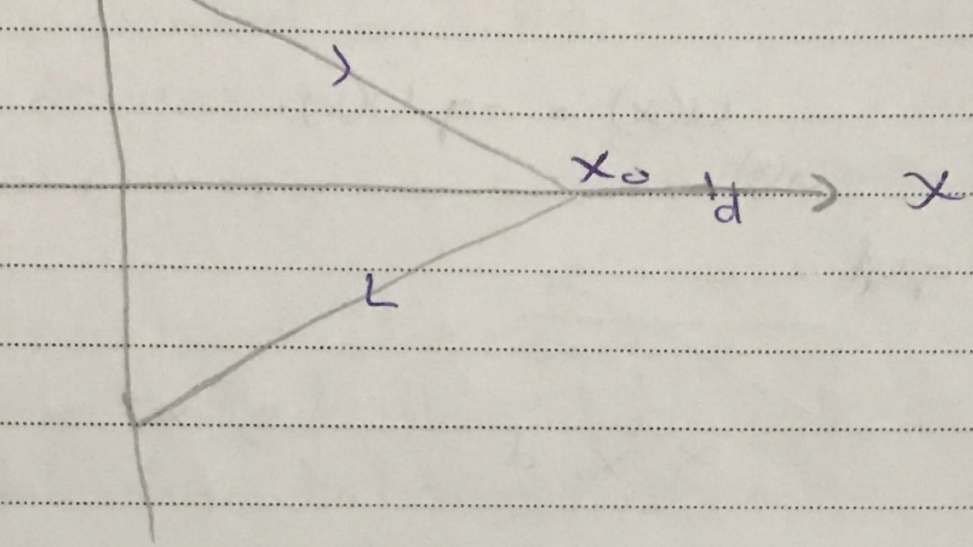
* Total energy of electrons remains the same

$$w = u + k = -qU(x) + \frac{1}{2}mv^2 = \text{constant}$$
$$\text{max } k \text{ at } A(x=0) = \frac{1}{2}mv^2 = w$$
$$\text{min } k \text{ at } x_0 = d \Rightarrow w = u$$

$\Rightarrow x_0$ = maximum distance the electron travel

\Rightarrow The alteration of direction of motion of electron at x_0 is a result of the potential energy barrier.

u_0 $U(x)$ speed electronics



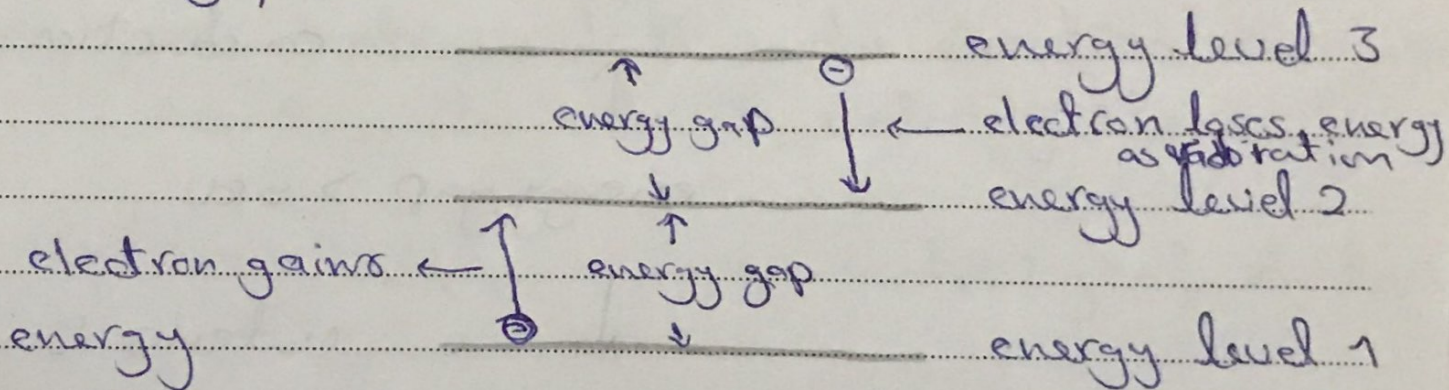
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Energy levels :-

In an isolated atom each energy level is associated with orbiting electrons.

These energy levels are discrete.

⇒ between energy levels are energy gaps in which no electrons exist.

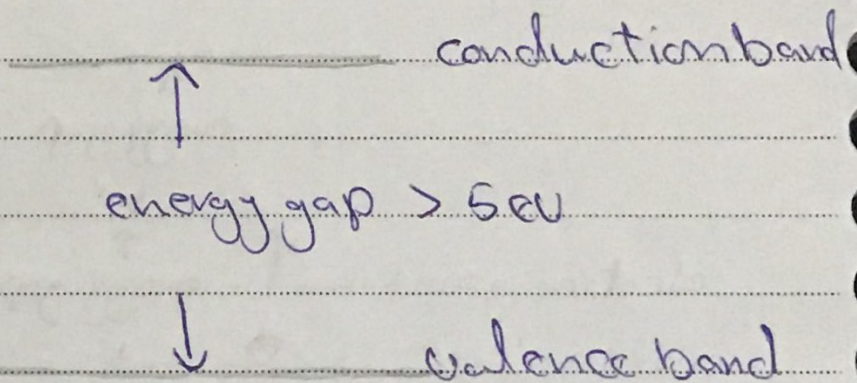


- The Transition from high to low energy level, the electron ~~gains~~ loses energy when as in transition from lower to high energy level, the electron gains energy.

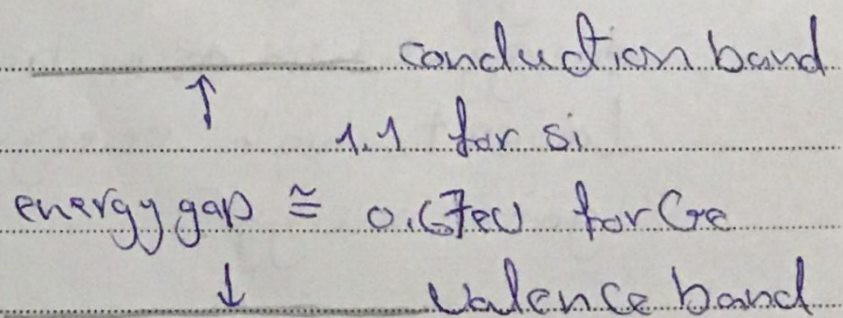
when atoms are brought to form crystals, the discrete energy levels in the atoms are expanded into energy bands.

Two important bands are the ^{valence} valence band and conduction band.

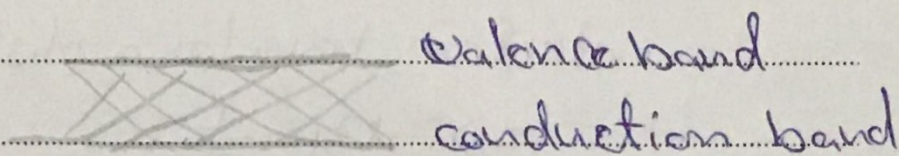
di'g insulator :-



Some conductors:-

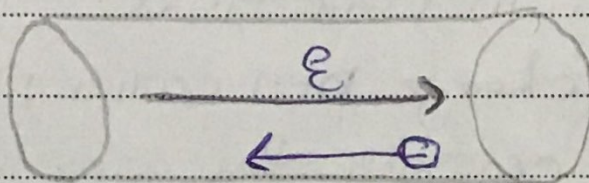


* Conductors :-



$$E_g = 0$$

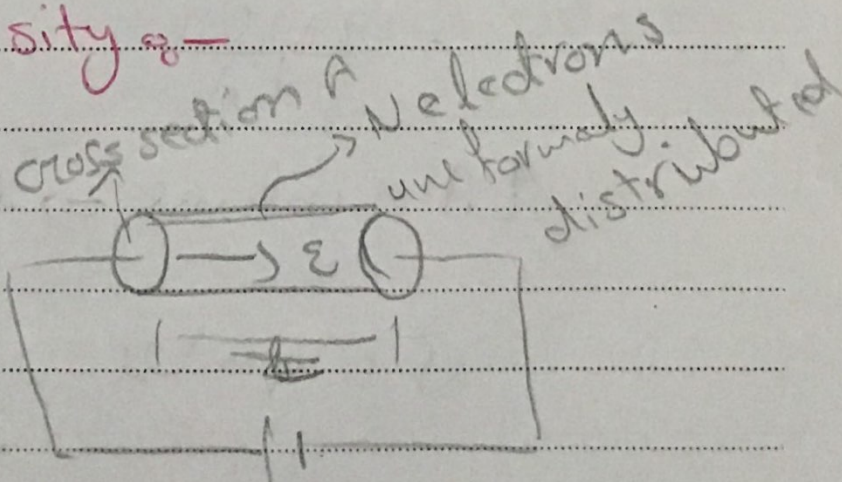
Free electron in an electric field E



The electrons drift in the direction opposite to E with a drift velocity U_d .

$$U_d = \mu_e E, \quad \mu_e = \text{mobility of electron}$$

* Current density :-



$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

under the influence of the field, an electron travels a distance L in time T

$$\Rightarrow v_d = \frac{L}{T}$$

I = current = Total charge crossing an area in unit time
 = (charge per carrier) \times (# of carriers crossing the area in unit time)

$$= q \times \frac{N}{T} = \frac{qN}{T} \cdot \frac{L}{L} = \frac{qNv_d}{L}$$

J = current density = $\frac{\text{current}}{\text{unit Area}}$

$$= \frac{I}{A} \text{ Amp/m}^2$$

$$= \frac{qNv_d}{LA}$$

LA = volume $\Rightarrow \frac{N}{LA}$ = concentration

$$J = qn v_d, \quad v_d = \mu E$$

$$\bar{J} = qn\mu E \quad \text{Amp/m}^2$$

The conductivity $= \sigma = qn\mu$

$$\bar{I} = \bar{J}A = \sigma E A \cdot \frac{L}{L} = \frac{\sigma A}{L} (EL)$$

$$\boxed{= \frac{\sigma A}{L} V = \frac{V}{R}} \rightarrow *$$

$$R = \frac{L}{\sigma A} = \rho \frac{L}{A}, \quad \rho = \text{resistivity (}\Omega\text{-m)}$$

$$\sigma = \frac{1}{\rho}$$

Example :-

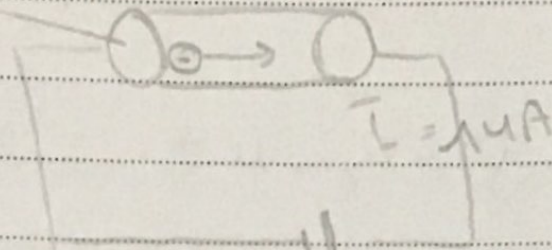
a copper conductor of 10^{-6} cross-section carries a 4 Amp current. determine the average electron drift velocity

Given $\rho = 1.73 \times 10^{-8} \Omega\text{-m}$

copper density = 8.9 g/cm^3

atom weight = 63.6

$$10^{-6} \text{ m}^2$$



$$V_d = \frac{IL}{qnA} = \frac{IV}{qnA}$$

$$V_d = \frac{IL}{qn} = \frac{J}{nq}$$

$$= \frac{J}{nq}$$

$$J = \frac{I}{A} = \frac{4 \text{ Amp}}{10^{-6} \text{ m}^2} = 4 \times 10^6 \text{ Amp/m}^2$$

find n :-

1 mole of copper = 63.6 grams

\Rightarrow 63.6 grams of copper contains 6.022×10^{23} atoms

each copper atom contributes are free electron

$\Rightarrow n = \#$ of free electrons in 1 m^3
 $= \#$ of atom in 1 m^3

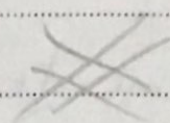
$$\text{Volume of 1 mole} = \frac{63.6 \text{ cm}^3}{8.9} = 7.14$$

$$1 \text{ m}^3 \text{ contains} = \frac{10^6 \times 8.9}{63.6} \text{ moles}$$

$$n = \frac{10^6 \times 8.9}{63.6} \times 6.022 \times 10^{23} = 8.43 \times 10^{28} \text{ electrons}$$

$$\therefore v_d = \frac{4 \times 10^6}{8.43 \times 10^{28} \times 1.6 \times 10^{-19}} = \frac{4}{8.43 \times 1.6}$$

$$\approx 3 \times 10^{-4} \text{ m/s}$$



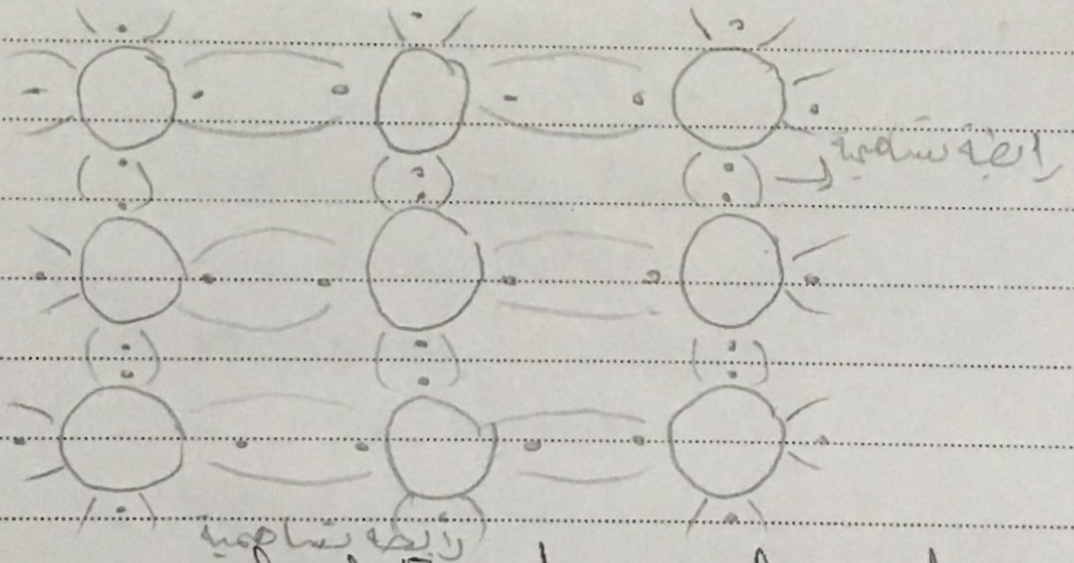
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مادة
التي يتم فصلها

* Semiconductor materials :-

① elemented semi conductors

- Silicon (Si) & Germanium (Ge)
- each atom contain 4 valance electrons
- Crystal structure of Si & Ge



② compound semi conductor

Breaking The covalent bond (freeing electrons) :-

* at 0K (-273°C):

covalent Bonds are very strong
(Not possible to free electrons).

\Rightarrow semiconductor is an insulator.
- it's necessary to free electrons
to make semiconductor suitable for
conduction.

\Rightarrow This requires amount of energy is
The energy gap E_g .

$E_g \cong 1.1\text{eV}$ for Si & $E_g \cong 0.67\text{eV}$ for Ge

* at room temperature (300K):

a small of electrons possess this amount
of energy & Break the covalent Bonds
and become free.

- holes:- when an electrons Becomes free
it leave behind a hole.

hole behaves a (+) charge.

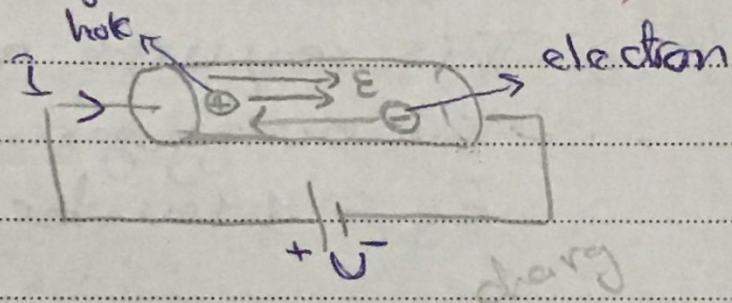
* النجاة من النار الا اذا احياها الله

- **Generation (Breaking of a bond) :-**
resulting in a free electron & a hole

الانقسام
- **Recombination :-**

Reconstructing the covalent Band.

- in a present of electric field (E)



$$J = (n\mu_n + p\mu_p) q E$$

$q = e =$ electric charge ($1.6 \times 10^{-19} \text{ C}$)

$n =$ concentration of negatively charged carriers electrons

$p =$ concentration of positively charged carriers (holes)

$\mu_n =$ mobility of electrons.

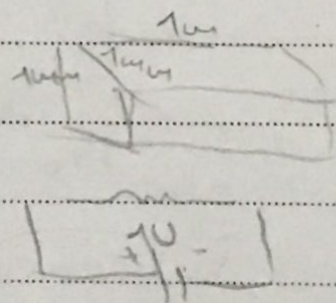
$\mu_p =$ mobility of holes.

Properties of semi conductor

Property	units	Si	Ge
Energy gap (E_g)	eV	1.1	0.67
μ_n	$\frac{cm^2}{V \cdot sec}$	1350	3900
μ_p	$\frac{cm^2}{V \cdot sec}$	480	1900
Intrinsic concentration (n_i)	# carriers cm^{-3}	1.5×10^{10}	2.4×10^{13}
resistivity ρ	$\Omega \cdot m$	2300	0.46
density (pure)	g/cm^3	2.33×10^6	5.32×10^6
atomic weight	$g/mole$	28.09	72.6

$R = \rho \frac{L}{A} = 2300 \times \frac{1}{10^{-8}} = 2.3 \times 10^9 \Omega$

التيار يكون صغيراً جداً لأن تركيز الحاملات
التي هي إلكترونات وفجوات منخفضة جداً



- Intrinsic Si & Ge have very low conductivity because concentration of mobile carriers (electrons & holes is very low).

- In intrinsic semiconductor each free electron creates a hole.

$$\Rightarrow n = p = n_i$$

\hookrightarrow intrinsic concentrations

At equilibrium, The number of electrons hole pairs is constant.

Example:-

ratio of electron-holes pairs to the # of atoms in Si.

$$\frac{\# \text{ of atoms}}{\text{m}^3} = \frac{2.33 \times 10^6}{28.08} \times 6.022 \times 10^{23}$$

atomic weight

$$\approx 5 \times 10^{28} = N$$

$$n_i = 1.5 \times 10^{16} / \text{m}^3$$

$$\frac{N}{n_i} = 3.3 \times 10^{12}$$

النسبة

كل 3.3×10^{12} ذرة سليكون يوجد زوج إلكترون-فجوة واحد

Intrinsic conductivity σ_i :-

$$\sigma_i = (n\mu_n + p\mu_p)e = n_i(\mu_n + \mu_p)e$$

$$= 1.5 \times 10^{16} * (0.135 + 0.048) * 1.6 \times 10^{19}$$

$$= 4.476 \times 10^{-4} / \Omega \cdot \text{m}$$

$$\rho_i = \frac{1}{\sigma_i} \approx 2.28 \times 10^3$$

11/3/2017

Extrinsic semiconductors:-

- conductivity of semiconductor can be changed by adding impurities to an intrinsic semiconductor (semiconductor becomes extrinsic or doped semiconductor)
- The impurities in an elemental semiconductor are most often trivalent or pentavalent atoms.
 ثلاث التكافؤ خمس التكافؤ
- In elemental semiconductor.
 - base material are the 4th column element
 - Trivalent element are 3rd column element
 - pentavalent elements are 5th column elements

• (+3) •

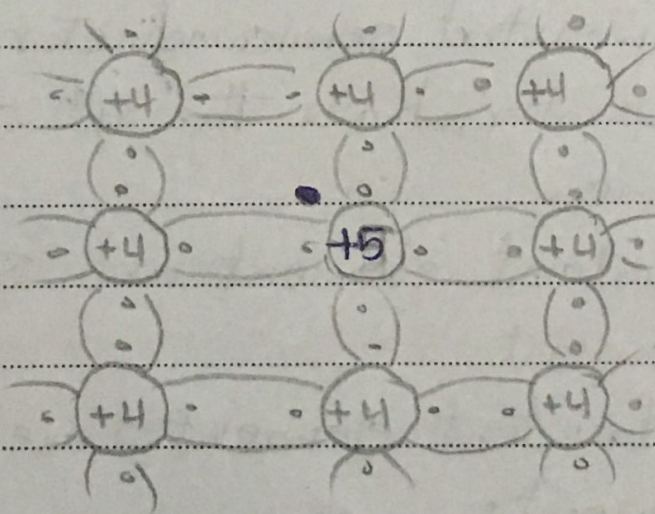
• (+4) •

• (+5) •

Boron (B)	Carbon (C)	Nitrogen (N)
Aluminum (Al)	Silicon (Si)	Phosphorus (P)
Gallium (Ga)	Germanium (Ge)	Arsenic (As)
Indium (In)	Tin (Sn)	Antimony (Sb)

n-type semiconductors :-

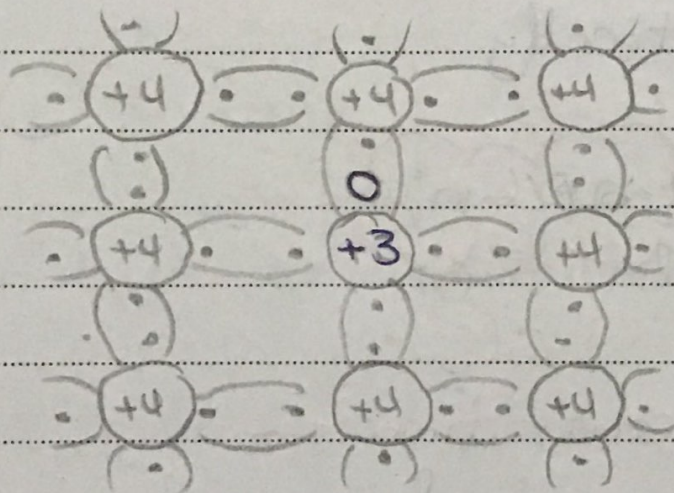
obtained by adding a 5th column element as impurity (doping element).



- only about 0.05 eV is needed to free the 5th electron of the Donor atom
- The 5th column element are called donor impurities or n-type impurities

\Rightarrow n increases $\Rightarrow \sigma$ increases
resulting semiconductor is called
n-type semiconductor

p-type semiconductors are
obtained by adding a 3rd column element
as impurity (doping element)



- The 3rd column element are called Acceptor impurities or p-type impurities

\Rightarrow p increases $\Rightarrow \sigma$ increases

resulting semiconductor is called p-type semiconductor.

* In n-type semiconductor:

- electrons are the majority carriers
- holes are the minority carriers

* In p-type semiconductor:

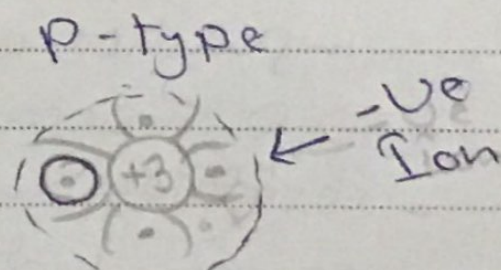
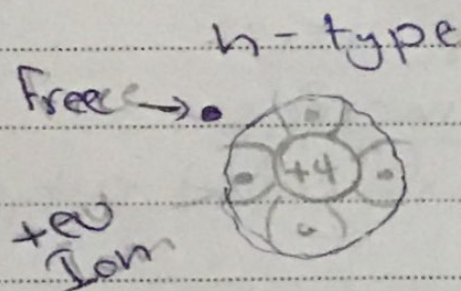
- holes are the majority carriers
- electrons are the minority carriers

- The mass action law is
Theoretically

$$np = n_i^2$$

- Carrier Concentration :-

small amount of energy is required to
ionize the impurity atoms.



- Virtually all impurity atoms are ionized at temperatures at which electronic devices are normally operated ($> 200^\circ\text{K}$).

- let N_D = concentration of Donor atoms.

N_A = concentration of acceptor atoms

- to maintain electric Neutrality.

- Total (+ve) charge = Total (-ve) charge

$$p + N_D = n + N_A$$

- In n-type semiconductor $N_A = 0$, $n \gg p$

$$\Rightarrow n \approx N_D$$

$$\Rightarrow p \approx n_i^2 / N_D$$

- In p-type semiconductor $N_D = 0$, $p \gg n$

$$\Rightarrow p \approx N_A$$

$$\Rightarrow n \approx n_i^2 / N_A$$

* Example:-

Determine the conductivity of a sample of a Si doped with Arsenic in which in every 10^6 atoms of Si, an arsenic

atom is added \Rightarrow n-type \Rightarrow 5th valence

$$\sigma = (n_n + p_p)q$$

semiconductor is n-type $\Rightarrow n = N_D$

given $N = 5 \times 10^{22}$ atom of Si cm^{-3}

$$\Rightarrow N_D = \frac{N}{10^6} = 5 \times 10^{16} \text{ atom of As/cm}^3$$

$$n = 5 \times 10^{16} \text{ free electrons/cm}^3$$

$$p = n_i^2 / N_D = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = \frac{2.25 \times 10^4}{5}$$

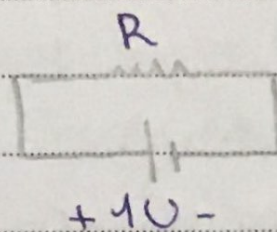
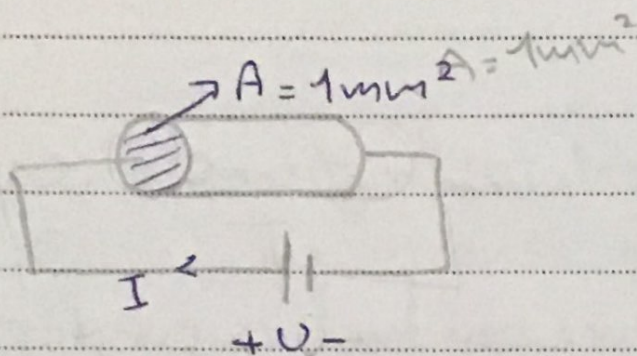
$$= 4.5 \times 10^3 \text{ holes/cm}^3$$

$$\sigma = 1.6 \times 10^{-19} \left(\frac{5 \times 10^{16}}{\text{cm}^3} \times \frac{1350 \text{ cm}^2}{\text{V-s}} + 4.5 \times 10^3 \right)$$

$$\times 480$$

$$\text{Let } \rho = 10.8 \text{ } \Omega\text{-cm}$$

Intrinsic



for intrinsic Si

$$R = \rho \frac{L}{A} = \rho \frac{10 \text{ cm}}{10^{-2} \text{ cm}^2} = \rho \frac{10^3}{\text{cm}} = 2280 \times 10^3 \Omega$$

$$\hat{I} = \frac{1}{R} = \frac{1}{2.28 \times 10^6} \text{ A} = \frac{1}{2.28} \mu\text{A}$$

$$R = \rho \frac{L}{A} = \rho \frac{10 \text{ cm}}{10^{-2} \text{ cm}^2} = 10^3 \rho = 10^3 \times 0.1 = 100 \Omega$$

$$\Rightarrow \hat{I} = \frac{1}{100} = 10 \text{ mA}$$

$$\text{Silicon } \rho = 10^5 = 38.4 / \Omega \cdot \text{cm} \text{ p.f.}$$

14/3/2017

Variation of semi conductors properties

$$\sigma = q (n\mu_n + p\mu_p)$$

for n-type, $n = N_D$, $p = n_i^2 / N_D$

for p-type, $p = N_A$, $n = n_i^2 / N_A$

μ_n , μ_p & n_i are properties of the materials.

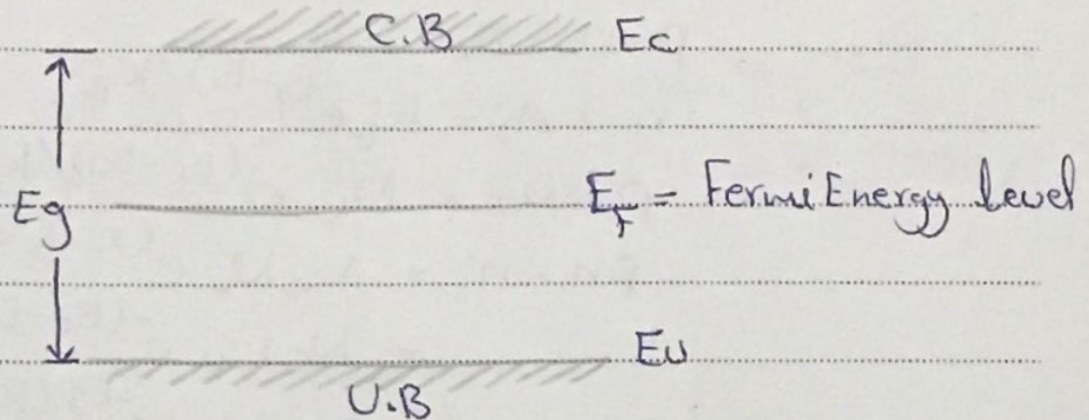
- n_i is function of temperature.
- μ_n & μ_p are functions in temperature & doping level, Electric field.

I) Variation of intrinsic concentration n_i with temperature T :-

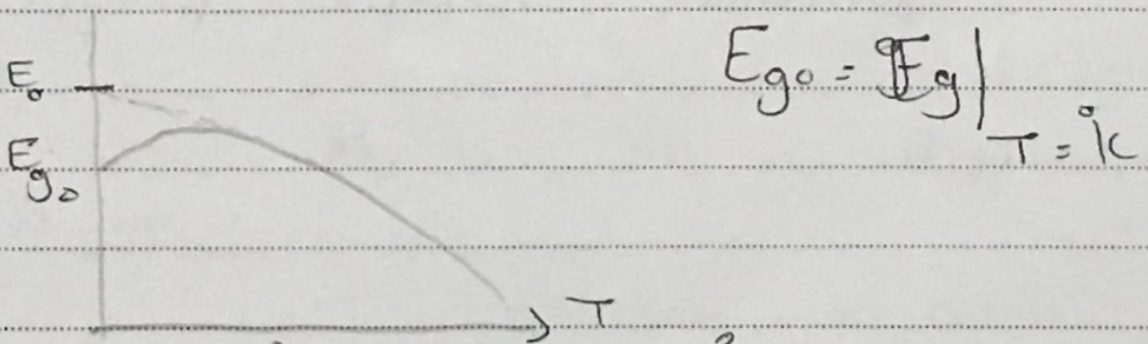
Some semiconductor physics results

- K_B = Boltzman constant = $1.381 \times 10^{-23} \text{ J/K}$
- h = Plank's constant = $6.626 \times 10^{-34} \text{ J-sec}$
- N_c = Density of states in the conduction Band

- N_v = Density of states in the valence band
- E_i = The intrinsic Fermi Energy level E_F



- $E_g \triangleq$ Energy gap ($E_c - E_v$)
- $E_g \cong E_{g_0} - b_i T$



$$N_c = 2 \left(\frac{2\pi m_e^* k_B T}{h^2} \right)^{\frac{3}{2}}$$

$$N_v = 2 \left[\frac{2\pi m_h^* k_B T}{h^2} \right]^{\frac{3}{2}}$$

$m_e^* \triangleq$ effective mass of electron

$m_h^* \triangleq$ effective mass of hole

* for intrinsic semiconductor :-

$$p = n = n_i$$

$$n = n_i = N_c e^{-(E_c - E_i)/k_B T}$$

$$p = n_i = N_v e^{-(E_i - E_v)/k_B T}$$

$$pn = n_i^2 = N_c N_v e^{(E_i - E_c + E_v - E_i)/k_B T}$$

$$= N_c N_v e^{-(E_c - E_v)/k_B T}$$

$$= N_c N_v e^{-E_g/k_B T}$$

$$\Rightarrow n_i = \sqrt{N_c N_v} e^{-E_g/2k_B T}$$

intrinsic

n-type

p-type

$E_F = E_i$

E_F

E_c

E_F E_v

$$N_v N_c = \left(2 \left[\frac{2\pi m_h^* k_B T}{h^2} \right] \right)^{3/2} \left(2 \left[\frac{2\pi m_e^* k_B T}{h^2} \right] \right)^{3/2}$$

$$= 4 \left(\frac{2\pi k_B T}{h^2} \right)^3 (m_h^* m_e^*)^{3/2}$$

$$\sqrt{N_c N_v} = 2 \left(\frac{2\pi k_B T}{h^2} \right)^{3/2} (m_h^* m_e^*)^{3/4}$$

$$\sqrt{N_c N_v} = k_2 T^{3/2}, \quad k_2 = 2 \left(\frac{2\pi k}{h^2} \right)^{3/2} (m_h^* m_e^*)^{3/4}$$

$$n_i = k_2 T^{3/2} e^{-E_g/(2k_B T)}$$

* for Si $\Rightarrow n_i(T) \cong 1.76 \times 10^{16} T^{3/2} e^{-\frac{4550}{T}} / \text{cm}^3$

* for Ge $\Rightarrow n_i(T) \cong 3.88 \times 10^{16} T^{3/2} e^{-\frac{7000}{T}} / \text{cm}^3$

* II) carrier mobility variations

Carrier mobility is affected by by carrier scattering mainly [lattice & ionized impurity scattering].

- For $T: 100 \rightarrow 400\text{K}$ $\mu \propto T^{-1/2}$ $m=2.5$ for Si

$\Rightarrow \mu$ decreases with increasing temperature T because

as T increases \Rightarrow more carriers
 \Rightarrow more collisions \Rightarrow lower mobility

- depend of μ on electric field E

• μ_n is constant for $E < 10^3 \text{ V/cm}$

• $\mu_n \propto \sqrt{E}$ for $10^3 \leq E < 10^4 \text{ V/cm}$

- mobility also function of doping level.

* Conductivity variation

n_i increases with T

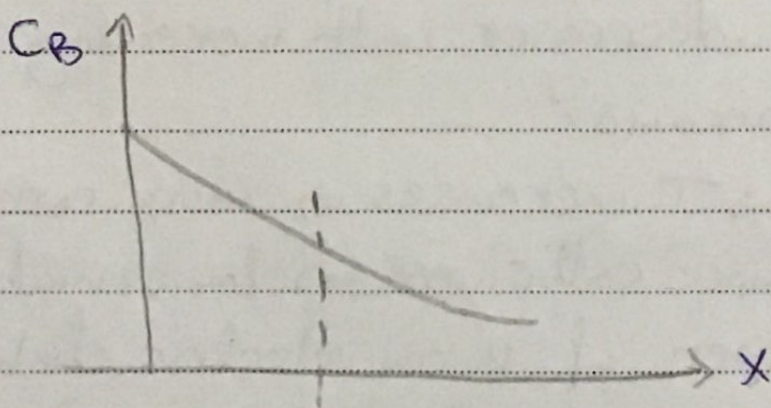
μ decreases with T

$|\Delta n_i| > |\Delta \mu| \Rightarrow \sigma_i$ increases with T

$$\sigma_i = n_i (\mu_n + \mu_p) q$$

* ~~D~~ Current flow by diffusion :-

انتشار Diffusion of particles occurs in the direction of -ve Gradient of particle concentration



Particle diffuse from left to right crossing the surface @ x_0

Particle flux across a surface at x_0 defined as the net number of particles crossing the surface per unit area per unit time

$$\text{i.e. particle flux} = F_0 = -D \frac{dC_B}{dx}$$

$$\frac{dC_B}{dx} = \text{concentration gradient}$$

$D \triangleq$ Diffusivity / Diffusion coefficient /
Diffusion constant

In-3D $C_B = C_B(x, y, z) \Rightarrow F_0 = F_0(x, y, z)$

$$F_0 = -D \underbrace{\nabla C_B}_{\text{Gradient of } C_B}$$

$$\nabla C_B = \left[\frac{\partial C_B}{\partial x}, \frac{\partial C_B}{\partial y}, \frac{\partial C_B}{\partial z} \right]$$

\Rightarrow Diffusion current density $= J_p = q(-D \nabla C_B)$
if particles are electrons $\Rightarrow J_{nd} = q D \nabla C_B$
if particles are holes $\Rightarrow J_{pd} = -q D \nabla C_B$

* Einstein's relation :-

relation between μ & D

current density has a drift component & diffusion component.

for electrons in n-type

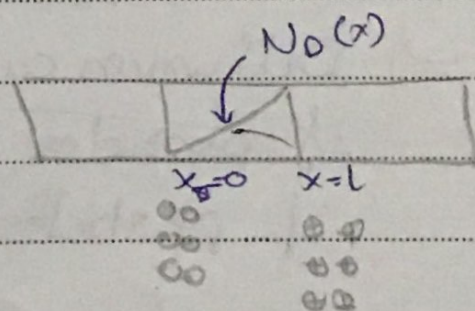
$$J_n = \underbrace{q \mu_n n E}_{\text{Drift component}} + \underbrace{q D_n \nabla n}_{\text{Diffusion component}}$$

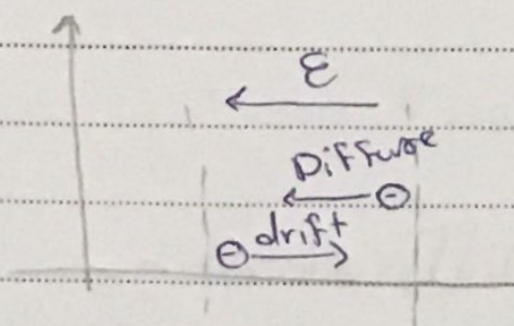
Consider a nx - unit uniformly doped n-type semiconductor

$$n = N_D \Rightarrow n(x) \approx N_D(x)$$

$$\nabla n = \frac{dn}{dx}$$

Electrons diffuse to the left of $x=l$ leaving behind ionized donors and causing some electrons to accumulate at $x=0$





21/3/2017

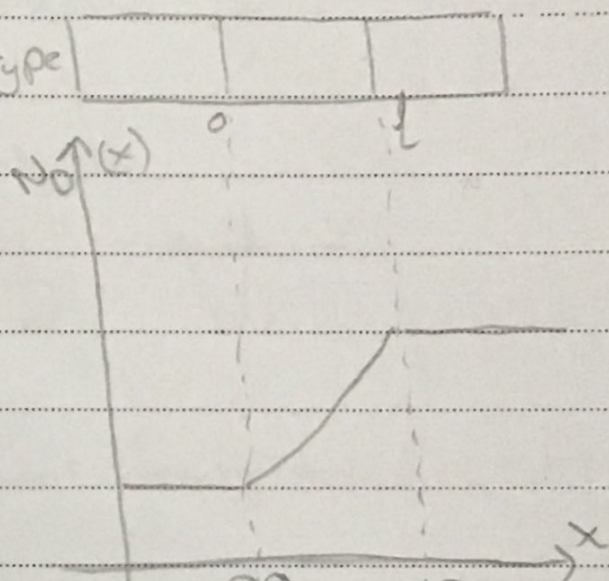
current flow by diffusion :-

For $0 \leq x \leq l$, cause
with x $N_D(0) = N_1$

$$N_D(l) = N_2$$

$$n(x) = N_D(x)$$

$$\nabla n = \frac{dn(x)}{dx}$$



In thermal equilibrium

- electrons diffuse from

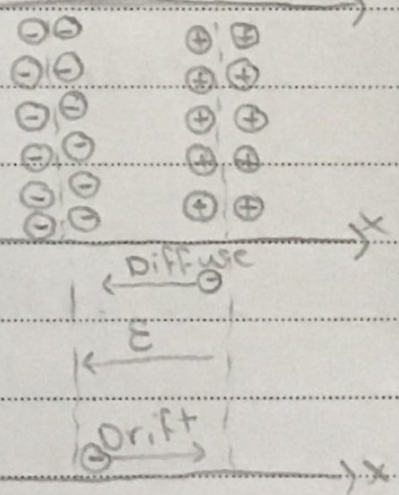
right to left

- electron drift from left

to right

But net current = 0

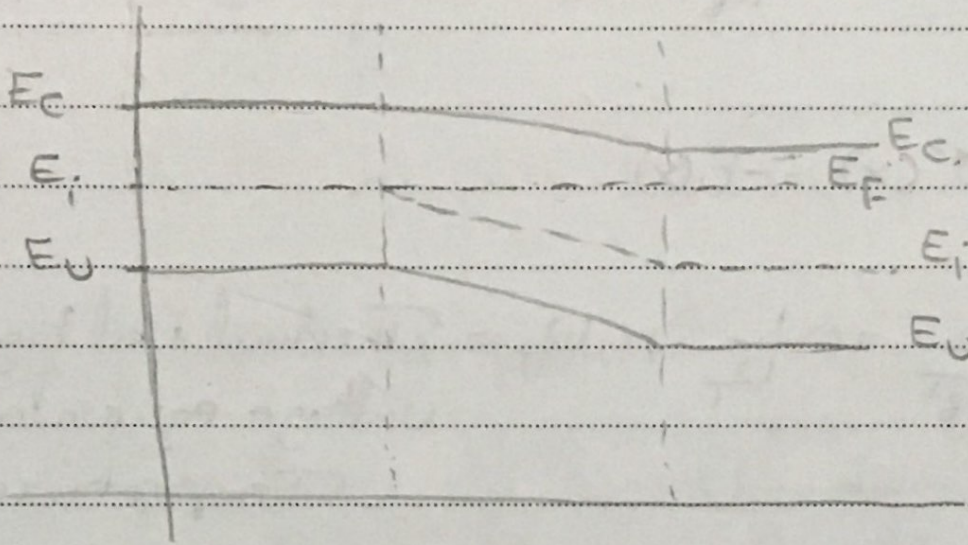
$$\Rightarrow J_n = 0$$



$$J_n = q \mu_n n E + q D \frac{dn}{dx} = 0 \text{ @ any } (x)$$

Energy band Diagram :-

Let $N_A = n_i$



E_F = Fermi Energy level

E_i = Intrinsic Fermi energy level

E_C = Bottom of conduction Band

E_V = Top of valence Band Energy level

$$n = n_i e^{(E_F - E_i(x)) / k_B T}$$

$$E_i(x) = -q \phi(x)$$

$$E_F - E_i(x) = E_i(0) - E_i(x) = -q[\phi(0) - \phi(x)]$$

$$\text{Let } \phi(0) = 0 \Rightarrow E_F - E_i(x) = q\phi(x)$$

$$n = n_i e^{q\phi(x)/k_B T}$$

$$\Rightarrow \frac{dn}{dx} = \frac{qn_i}{k_B T} e^{q\phi(x)/k_B T} \overbrace{\frac{d\phi(x)}{dx}}^{\phi'(x)} = \frac{q}{k_B T} n \phi'(x)$$

$$\phi'(x) = -E(x)$$

$$\frac{q}{k_B T} = \frac{1}{V_T}, \quad V_T = \text{Thermal voltage or voltage equivalent of Temperature}$$

$$\text{@ room temperature } V_T = 0.02568 \text{ V} = 25.68 \text{ mV}$$

Back to in thermal equilibrium :-

$$q D_n \frac{dn}{dx} = q D_n \frac{q}{k_B T} n \phi'(x) = -q \frac{D_n n E}{V_T}$$

$$J_n = q \mu_n n E - q \frac{D_n}{V_T} n E = q n E (\mu_n - D_n / V_T) = 0$$

$$\mu_n - \frac{D_n}{U_T} = 0 \Rightarrow \left(\frac{D_n}{\mu_n} = U_T \right) \text{ Einstein's relation}$$

also $D_p/\mu_p = U_T$

The Built-in potential $\phi(x)$:-

$$J_n = q D_n \frac{dn}{dx} + q \mu_n n E = 0$$

$$E = - \frac{D_n}{n \mu_n} \frac{dn}{dx} = - \frac{U_T}{n} \frac{dn}{dx}$$

$$\text{But } E = - \frac{d\phi(x)}{dx} \Rightarrow - \frac{d\phi(x)}{dx} = - \frac{U_T}{n} \frac{dn}{dx}$$

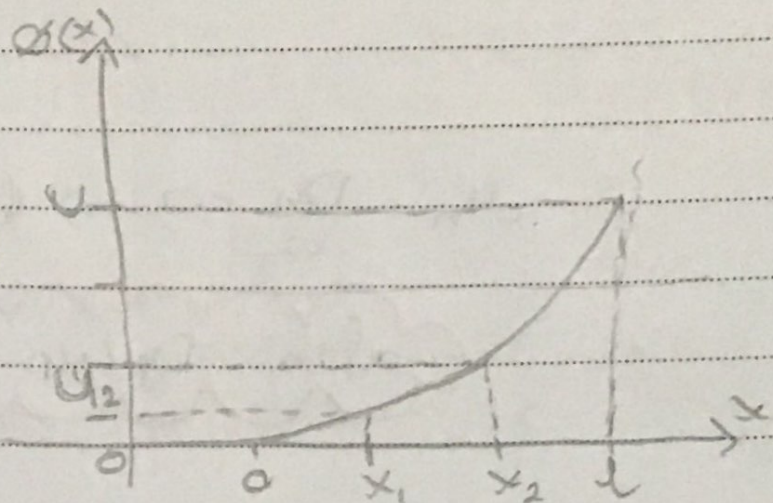
$$\Rightarrow d\phi(x) = U_T \frac{dn}{n}$$

$$\phi(x) = \int_0^x d\phi(x) = U_T \int_{n(0)}^{n(x)} \frac{dn}{n} = U_T \left[\ln n(x) \right]_{n(0)}^{n(x)}$$

$$= U_T \left[\ln n(x) - \ln n(0) \right] = U_T \ln \left(\frac{n(x)}{n(0)} \right)$$

$$V = U_T \ln \left(\frac{n(x)}{n(0)} \right)$$

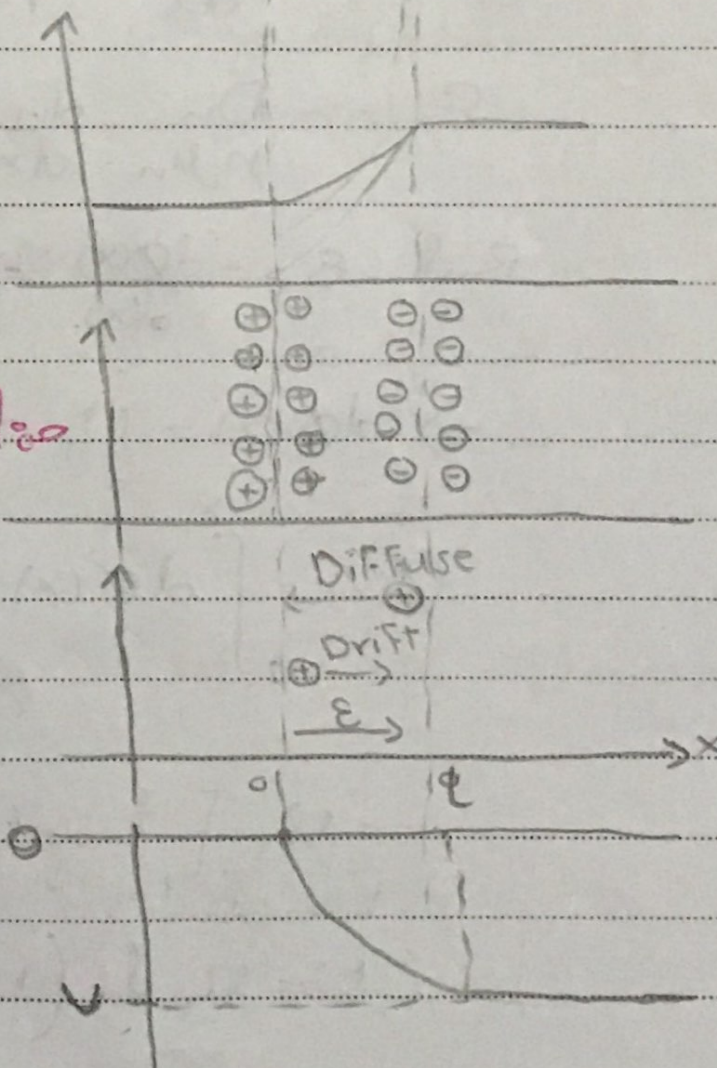
$$V_{12} = V_T \ln \frac{n(x_2)}{n(x_1)}$$



$$\phi(x) = -V_T \ln \left(\frac{P(x)}{P(0)} \right)$$

$$V = -V_T \ln \left(\frac{P(L)}{P(0)} \right)$$

P-type



For n-type materials

$$\text{Let } n(x) = n_i @ x = x_2$$

$$\Rightarrow V_{12} = \phi(x_2) - \phi(x_1)$$

$$= V_T \ln \left(\frac{n(x_2)}{n(x_1)} \right)$$

$$= V_T \ln \left(\frac{n_2}{n_1} \right)$$

$$\frac{V_n}{V_T} = \ln \frac{n_2}{n_1} \Rightarrow \frac{n_2}{n_1} = e^{V_n/V_T} \Rightarrow n_2 = n_1 e^{V_n/V_T}$$

$$n_1 = n_2 e^{-V_n/V_T}$$

For p-type :-

$$P(x_1) = P_1, P(x_2) = P_2$$

$$V_p = \phi(x_2) - \phi(x_1) = -V_T \ln \frac{P(x_2)}{P(x_1)}$$

$$= -V_T \ln \frac{P_2}{P_1} \Rightarrow \frac{P_2}{P_1} = e^{-V_p/V_T}$$

$$\Rightarrow P_2 = P_1 e^{-V_p/V_T} \Rightarrow P_1 = P_2 e^{V_p/V_T}$$

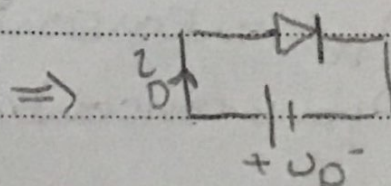
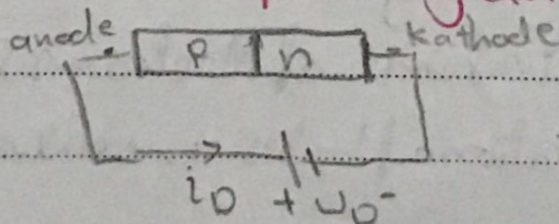
$$n_2 P_2 = n_1 e^{V_n/V_T} P_1 e^{-V_p/V_T} = n_1 P_1 e^{(V_n - V_p)/V_T}$$

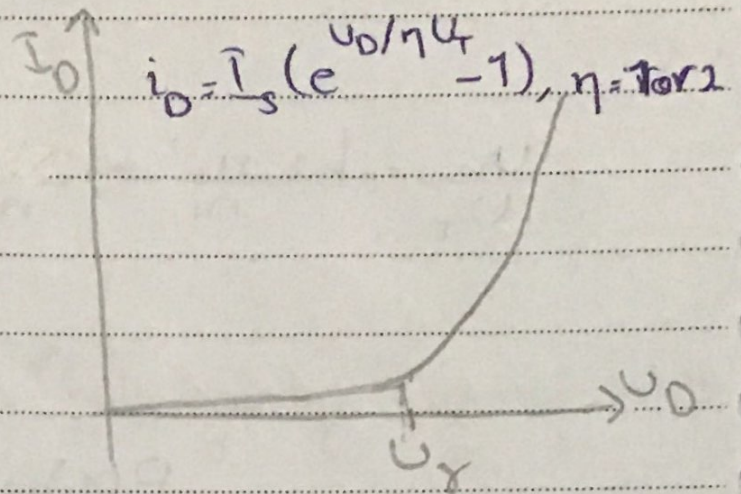
For the same type semiconductor

$$V_n = V_p$$

$$\Rightarrow n_2 P_2 = n_1 P_1 \Rightarrow np = n_i^2 \quad (\text{mass action law})$$

* The p-n junction :-





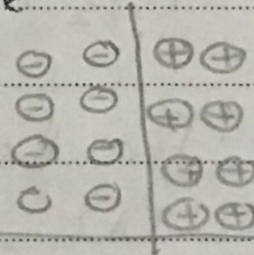
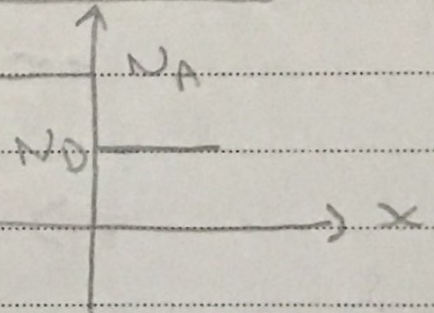
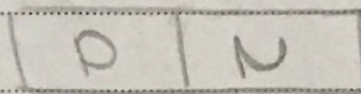
The step (abrupt) junction

- Carrier concentration

- holes diffuse from p

to n around the junction

- electrons diffuse in opposite direction.



Notation:-

n_{no} = concentration of electrons in neutral n-region.

p_{no} = concentration of holes in neutral n-region.

n_{po} = concentration of electrons in neutral p-region.

p_{po} = concentration of holes in neutral p-region.

P_p = concentration of holes in p-region

n_p = concentration of electron in p-region

n_n = concentration of electron in n-region

P_n = concentration of holes in n-region

$P_p = P_{p0}$ in neutral p-region = N_A

$n_n = n_{n0}$ in neutral n-region = N_D

$$\Rightarrow n_{p0} = \frac{n_i^2}{P_{p0}} = n_i^2 / N_A$$

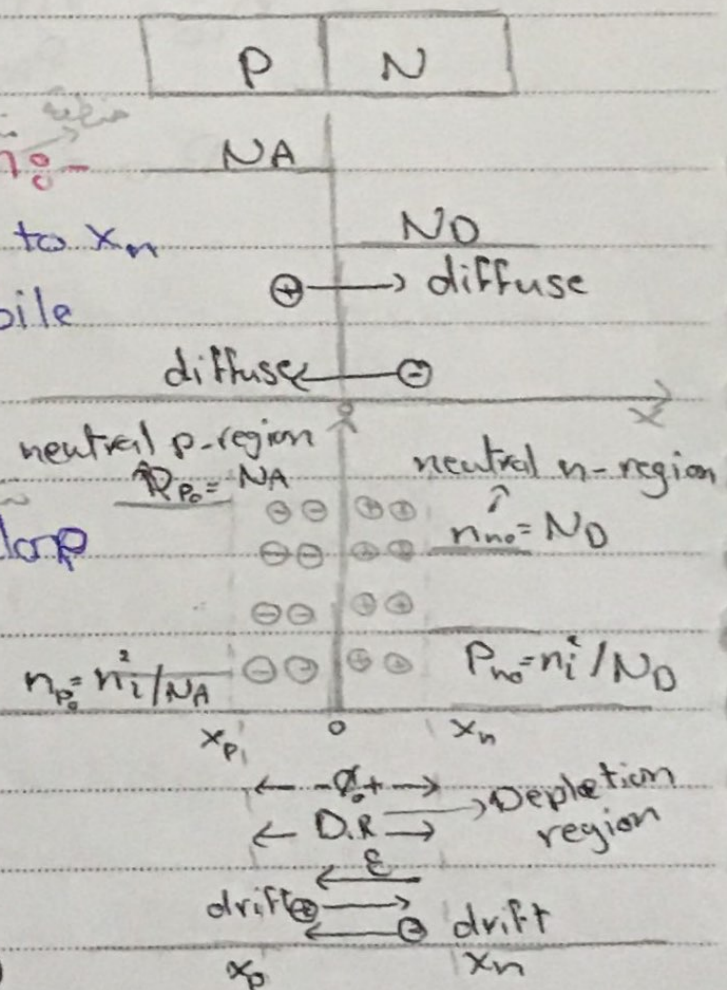
$$P_{n0} = n_i^2 / N_D$$

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- holes diffuse from left to right leaving behind (-ve) ions.
- electrons diffuse from right to left leaving behind (+ve) ions.

The depletion Region:

(Region from x_p to x_n Depleted from mobile charges)



- The ions on the sides of the junction develop a potential difference
- => Electric field develops across the junction.

=> This field is quite large, it sweeps away the mobile carrier from the depletion region.

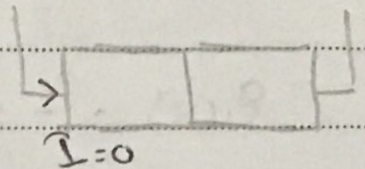
$d = \text{drift}$ $D = \text{Diffusion}$

At no external bias

No current flows

\Rightarrow net current density

$$= \bar{J} = 0$$



The equilibrium barrier potential (ϕ_0)

if it is built in potential about the junction ϕ_0 is developed such as that the drift current is just equals to the diffusion current to meet $\bar{J} = 0$

$$\bar{J} = \bar{J}_n + \bar{J}_p, \quad \bar{J}_n = \bar{J}_{nd} + \bar{J}_{no}, \quad \bar{J}_p = \bar{J}_{pd} + \bar{J}_{po}$$

$$\bar{J} = 0 \Rightarrow \text{Either } \bar{J}_n = \bar{J}_p \text{ or } \bar{J}_n = \bar{J}_p = 0$$

Consider $\bar{J}_p = 0 : (x_p \leq x \leq x_n)$

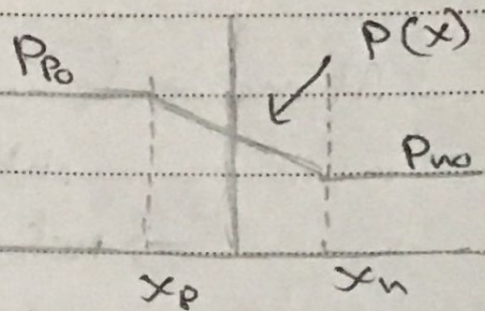
$$\Rightarrow \bar{J}_{pd} + \bar{J}_{po} = q \mu_p p(x) E(x) - q D_p \frac{dp(x)}{dx} = 0$$

$$E(x) = V_T \frac{dp(x)}{dx} \Rightarrow p(x) E(x) - \frac{D_p}{\mu_p} \frac{dp(x)}{dx} = 0$$

SS

$$P(x) E(x) = U_T \frac{dP(x)}{dx}$$

$$E(x) = - \frac{d\phi(x)}{dx}$$



$$\Rightarrow d\phi(x) = -E(x)dx = -U_T \frac{dP(x)}{P(x)}$$

$$\phi(x) = \int_{-\infty}^x d\phi(z) = \int_{-\infty}^{x_p} d\phi(z) + \int_{x_p}^x d\phi(z)$$

$$= \phi_p + \int_{x_p}^x d\phi(z)$$

$$= \phi_p - U_T \int_{x_p}^x \frac{dP(z)}{P(z)} = \phi_p - U_T \ln P(z) \Big|_{x_p}^x$$

$$\phi(x) = \phi_p - U_T \ln \frac{P(x)}{P(x_p)} = \phi_p + U_T \ln \frac{P(x_p)}{P(x)}$$

$$= \phi_p + U_T \ln \frac{P_0}{P(x)}$$

$$\textcircled{a} \quad x = x_1$$

at $x = x_n$

$$\phi(x) = \phi_n = \phi_p + V_T \ln \frac{p_{pe}}{p_{no}}$$

$$\phi_n = \phi_p + V_T \ln \frac{N_A}{n_i^2/N_D} = \phi_p + V_T \ln \frac{N_A N_D}{n_i^2}$$

$$\phi_o = \phi_n - \phi_p = V_T \ln \frac{N_A N_D}{n_i^2}$$

$$\phi_o = V_T \ln \frac{p_{pe} n_{no}}{n_i^2} \Rightarrow \frac{p_{pe} n_{no}}{n_i^2} = e^{\phi_o/V_T}$$

$$\phi_o = V_T \ln \frac{p_{pe}}{p_{no}} \Rightarrow \frac{p_{pe}}{p_{no}} = e^{\phi_o/V_T}$$

$$\Rightarrow p_{pe} = p_{no} e^{\phi_o/V_T}, \quad p_{no} = p_{pe} e^{-\phi_o/V_T}$$

Similarly :-

$$J_n = 0 \Rightarrow n_{no} = n_{po} e^{\phi_o/V_T}$$

$$n_{po} = n_{no} e^{-\phi_o/V_T}$$

Depletion \rightarrow Doping (di) Region \rightarrow ϕ_0

- The potential ϕ_0 present a barrier against further diffusion of majority carriers.

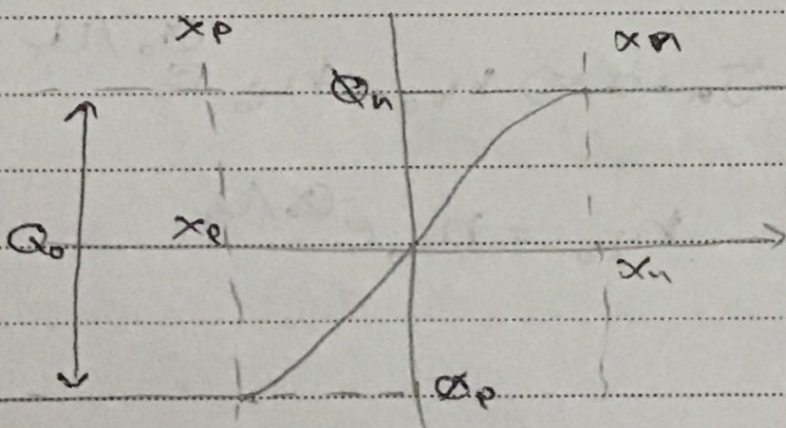
Examples \rightarrow

Determine ϕ_p , ϕ_n , ϕ_0 for a step Si P-n junction at 300K with $N_A = 10^{18}/\text{cm}^3$, $N_D = 10^{15}/\text{cm}^3$, Assume $n_i = 1.5 \times 10^{10}/\text{cm}^3$, $U_T = 26 \text{ mV}$

$$\phi_p = -U_T \ln \frac{N_A}{n_i} \cong -468 \text{ mV}$$

$$\phi_n = U_T \ln \frac{N_D}{n_i} \cong 289 \text{ mV}$$

$$\phi_0 = \phi_n - \phi_p \cong 0.757 \text{ V}$$



$$\Phi_0 = \Phi_n - \Phi_p = V_T \ln \frac{N_A N_D}{n_i^2}$$

$$= V_T \ln \frac{N_A}{n_i} - V_T \ln \frac{N_D}{n_i}$$

$$= \underbrace{V_T \ln \frac{N_A}{n_i}}_{\text{potential barrier}} + V_T \ln \frac{N_D}{n_i}$$

الباريكة الجهوية

* The depletion region charge is -

$$\Phi_0 \cong 100, \quad x_d < 1 \mu\text{m}$$

$$\Rightarrow E \cong 10^5 \text{ V/cm in the depletion region}$$

توزيع الأيونات الثابتة

* distribution of immobile ions is -

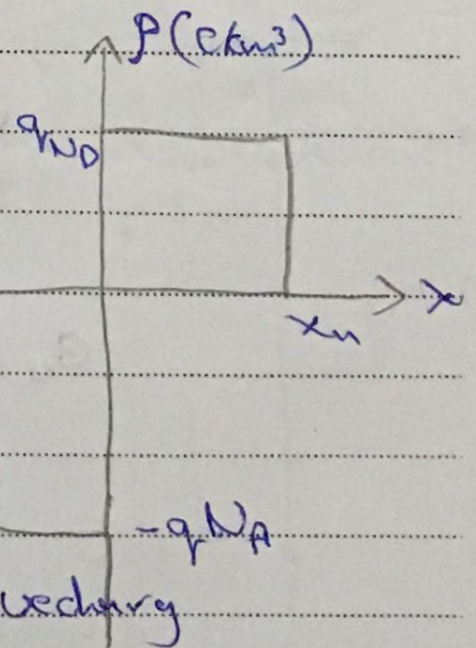
« No mobile charges »

for $x_p < x < 0$

charge density $\rho = -qN_A$

for $0 < x < x_n \Rightarrow \rho = qN_D$

also assume depletion is



\Rightarrow Total charge +ve = Total -ve charge

$$\Rightarrow qN_p (Ax_n) = -qN_A (Ax_p), \quad x_n > 0, \quad x_p < 0$$

$$N_p x_n = N_A |x_p| \Rightarrow N_p |x_n| = N_A |x_p|$$

The electric field $E(x)$:-

$$E = 0 \text{ for } x \leq x_p \text{ \& } x \geq x_n$$

$$\text{from Gauss' law: } \frac{dE(x)}{dx} = \rho / \epsilon$$

ρ = charge density

ϵ = Dielectric permittivity of the material = $\epsilon_r \epsilon_0$

ϵ_r = relative dielectric permittivity of the material

material	Si	Ge	GaAs
ϵ_r	11.68	16.2	12.9

$$\epsilon_0 = \text{permittivity of free space}$$

$$= 8.85 \times 10^{-14} \text{ F/cm}$$

28/3/2017

The electric field:-

$$E=0 \text{ for } x \leq x_p \text{ \& } x \geq x_n$$

$$\frac{dE(x)}{dx} = \rho/\epsilon \Rightarrow dE(x) = \frac{\rho}{\epsilon} dx$$

$$\rho=0 \text{ for } x \leq x_p \text{ \& } x \geq x_n \Rightarrow E(x)=0$$

for $x_p \leq x \leq 0$:

$$\rho(x) = -qN_A$$

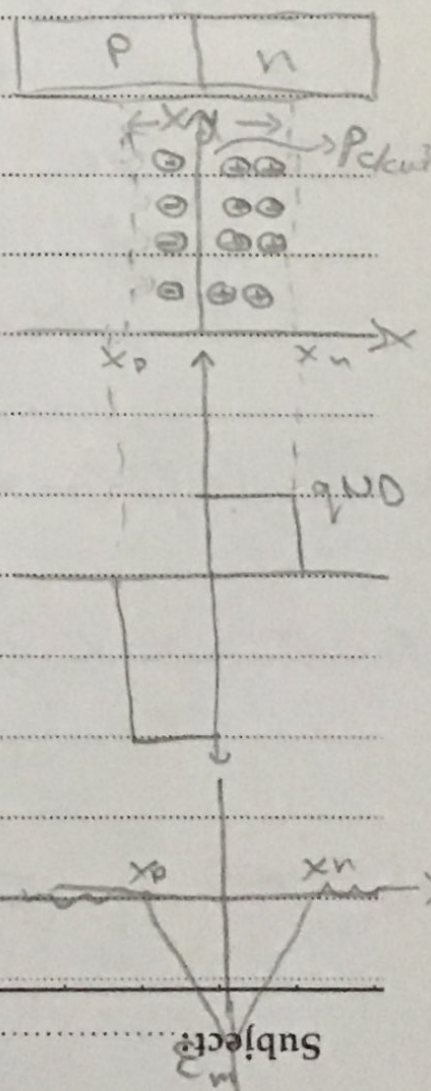
$$E(x) = \int_{x_p}^x \frac{\rho}{\epsilon} dx$$

$$= -\frac{qN_A}{\epsilon} \int_{x_p}^x dx = -\frac{qN_A}{\epsilon} (x - x_p)$$

$$\text{@ } x=0 \quad E(x) = \frac{qN_A x_p}{\epsilon}$$

for $0 < x \leq x_n$

$$E(x) = E(0) + \int_0^x \frac{\rho N_D}{\epsilon} dx$$



Subject

$$\Rightarrow E_0 + \frac{qND}{\epsilon} \int_0^x dx = E(0) + \frac{qND}{\epsilon} x$$

$$E(x) = \frac{qN_A x_p}{\epsilon} + \frac{qN_D x}{\epsilon}$$

$$\textcircled{a} \quad x = x_n, \quad E = 0$$

$$0 = \frac{qN_A x_p}{\epsilon} + \frac{qN_D x_n}{\epsilon}$$

$$E_m = E(0) = \frac{qN_A x_p}{\epsilon} = -\frac{qN_D x_n}{\epsilon}$$

for $x_p \leq x \leq 0$

$$E(x) = -\frac{qN_A}{\epsilon} (x - x_p)$$

$$= \frac{qN_A}{\epsilon} (x - x_p)$$

$$= \frac{qN_A x_p}{\epsilon} - \frac{qN_A x}{\epsilon}$$

$$= E_m - \frac{qN_A x}{\epsilon}$$

$$= E_m - \frac{qN_A x_p}{\epsilon x_p} x$$

$$E_m = (1 - x/x_p)$$

for $0 \leq x \leq x_n$

$$E(x) = E_m + \frac{qN_D x}{\epsilon} = E_m + \frac{qN_D x_n x}{\epsilon x_n}$$

$$E(x) = E_m (1 - x/x_n)$$

$$\therefore E(x) = \begin{cases} 0 & \text{for } x \leq x_p \text{ \& } x \geq x_n \\ E_m(1 - x/x_p) & \text{for } x_p \leq x \leq 0 \\ E_m(1 - x/x_n) & \text{for } 0 \leq x \leq x_n \end{cases}$$

$$E_m = \frac{qN_A x_p}{\epsilon} = -\frac{qN_D x_n}{\epsilon}$$

since $E(x) = -d\phi(x)/dx \Rightarrow \phi(x) = -\int E(x) dx$

$$\textcircled{a} \ x = x_p, \phi(x) = \phi_p \text{ \& } \textcircled{a} \ x = x_n, \phi(x) = \phi_n$$

for $x_p \leq x \leq 0$

$$\phi(x) = \phi_p - \int_{x_p}^x E(x) dx = \phi_p - \int_{x_p}^x E_m \left(1 + \frac{x}{x_p}\right) dx$$

$$\phi(x) = \phi_p - \epsilon_m \int_{x_p}^x (1 - x/x_p) dx$$

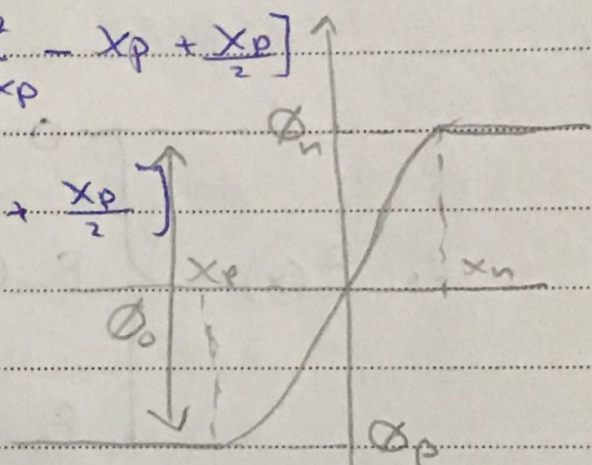
$$= \phi_p - \epsilon_m \left[x - \frac{x^2}{2x_p} \right]$$

$$= \phi_p - \epsilon_m \left[\left(x - \frac{x^2}{2x_p} \right) - \left(x_p - \frac{x_p^2}{2x_p} \right) \right]$$

$$\phi(x) = \phi_p - \epsilon_m \left[x - \frac{x^2}{2x_p} - x_p + \frac{x_p}{2} \right]$$

$$\phi(x) = \phi_p + \epsilon_m \left[\frac{x^2}{2x_p} - x + \frac{x_p}{2} \right]$$

for $0 \leq x \leq x_n$



$$\phi(x) = \phi(0) - \int_0^x \epsilon(x) dx$$

$$\text{① } x=0, \phi(0) = \phi_p + \epsilon_m \frac{x_p}{2} = 0$$

$$\phi_p = -\frac{\epsilon_m x_p}{2}$$

By the same arg^t you can show that

$$\phi_n = \frac{E_m x_n}{2}$$

can also show that

$$\phi(x) = \frac{q N_A X_p}{2\epsilon} (x x_p - x^2/2) \text{ for } x_p \leq x \leq 0$$

$$\Rightarrow \phi_p = \frac{-q N_A X_p^2}{2\epsilon}$$

$$\phi_n = \frac{-E_m x_n}{2} = \frac{q N_D X_n^2}{2\epsilon}$$

$$\phi(x) = \frac{q N_D}{\epsilon} (x x_n - x^2/2) \text{ for } 0 \leq x \leq x_n$$

$$\phi_0 = \phi_n - \phi_p = \frac{q N_D X_n^2}{2\epsilon} + \frac{q N_A X_p^2}{2\epsilon}$$

$$= \frac{q}{2\epsilon} [N_D X_n^2 + N_A X_p^2]$$

The width depletion region is -

$$E_m = \frac{q N_A X_p}{\epsilon} = \frac{-q N_D x_n}{\epsilon}$$

في doping level (نسبة) $n \leq p$

$$\Rightarrow N_A |x_p| = N_D |x_n|$$

$$|x_p| = \frac{N_D}{N_A} |x_n|, \quad |x_n| = \frac{N_A}{N_D} |x_p|$$

$$\Rightarrow \phi_0 = \phi_n - \phi_p = \frac{q}{2\epsilon} \left[N_D x_n^2 + N_A \frac{N_D^2}{N_A} x_n^2 \right]$$

$$\phi_0 = \frac{q N_D x_n^2}{2\epsilon} \left[1 + \frac{N_D}{N_A} \right] = \frac{q x_n^2 N_D}{2\epsilon N_A} [N_A + N_D]$$

$$|x_n| = \sqrt{\frac{2\epsilon N_A \phi_0}{q N_D (N_A + N_D)}} \quad \text{also } |x_p| = \sqrt{\frac{2\epsilon \phi_0 N_D}{N_A q (N_A + N_D)}}$$

$$x_d = |x_n| + |x_p|$$

$$= \sqrt{\frac{2\epsilon \phi_0}{q (N_A + N_D)}} \sqrt{\frac{N_A}{N_D}} + \sqrt{\frac{2\epsilon \phi_0}{q (N_A + N_D)}} \sqrt{\frac{N_D}{N_A}}$$

$$= \sqrt{\frac{2\epsilon \phi_0}{q (N_A + N_D)}} \left\{ \sqrt{\frac{N_A}{N_D}} + \sqrt{\frac{N_D}{N_A}} \right\}$$

$$= \sqrt{\frac{2\epsilon \phi_0 (N_A + N_D)}{q N_A N_D}}$$

Can show that

$$E_m = \frac{-qN_D}{\epsilon} \sqrt{\frac{2\epsilon\phi_0 N_A}{qN_D(N_A+N_D)}} = \sqrt{\frac{2qN_A N_D \phi_0}{\epsilon(N_A+N_D)}}$$

$$|x_n| = x_d \left(\frac{N_A}{N_A+N_D} \right), \quad |x_p| = x_d \left(\frac{N_D}{N_A+N_D} \right)$$

The Depletion Region Charge q

$$Q = \int \rho dv = \rho v$$

→ cross section area

$$Q_j = -qN_A A |x_p| \leftarrow \text{neg charge}$$

$$= qN_D A |x_n| \leftarrow \text{+ve charge}$$

$$= AqN_D \sqrt{\frac{2\epsilon N_A \phi_0}{qN_D(N_A+N_D)}} = A \sqrt{\frac{2\epsilon q N_D N_A \phi_0}{N_A+N_D}}$$

The Junction Capacitance (Depletion layer cap.)

$$C_j = \frac{d\phi_j}{d\phi} \quad @ \text{ No external bias}$$

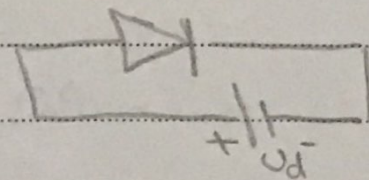
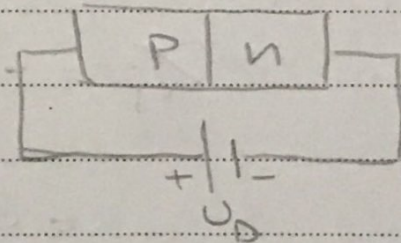
$$C_j = C_{j0}, \quad \phi = \phi_0$$

$$C_{j0} = \left. \frac{d\phi_j}{d\phi} \right|_{\phi=\phi_0} = A \sqrt{\frac{2\epsilon q N_A N_D}{N_A + N_D}} \frac{1}{\sqrt{\phi_0}}$$

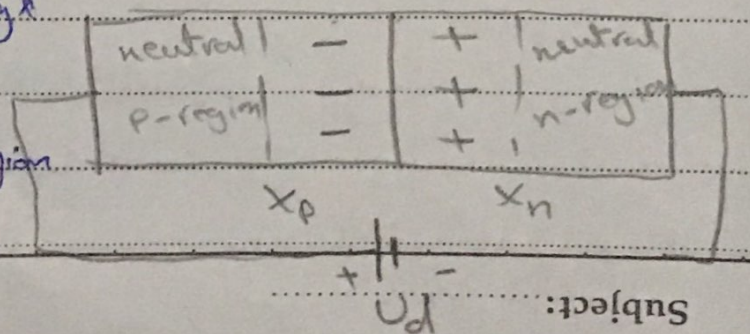
P-n junction with external bias

Assumption:- The external bias appears directly across the junction Depletion region

$$R_p \ll R_d, R_n \ll R_d$$

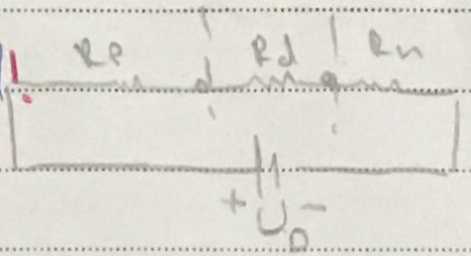


⇒ most of the voltage appears across R_d i.e. across the depletion region



تبعاً لـ (10-5) (A. 11)

what is the barrier potential!

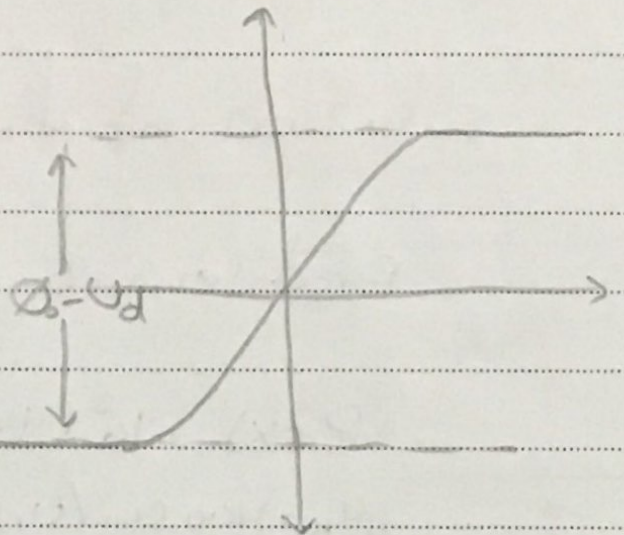


$$\phi = \phi_0 - U_d$$

in all formula

ϕ_0 is replaced by

$\phi_0 - U_d$ when the junction is biased by an external voltage U_d



28/3/2017

Tutorial

solution of home worke one :-

Problem 18 ng -

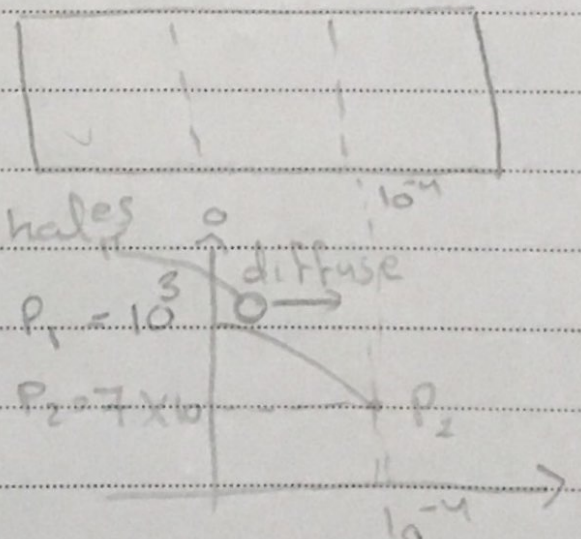
$$P(x) = 10^3 (1 - 3 \times 10^3 x) / \text{cm}^3, \quad 0 \leq x \leq 10^{-4} \text{cm}$$
$$\mu_n = 400 \text{ cm}^2/\text{V.s}, \quad \mu_p = 300 \text{ cm}^2/\text{V.s}$$

$$\textcircled{A} \quad \bar{J}_{\text{PDiff}} = \bar{J}_{\text{PDiffuse}} A$$

$$\bar{J}_{\text{PDiff}} = -q D_p \frac{dP}{dx}$$

$$\frac{D}{\mu} = V_T \Rightarrow D_p = V_T \mu$$

$$\frac{dP(x)}{dx} = -3 \times 10^6 \frac{\text{holes/cm}^3}{\text{cm}}$$



$$\textcircled{B} \quad V_1 = -V_T \ln\left(\frac{P_2}{P_1}\right) = -25 \ln\left(\frac{7 \times 10^2}{10^3}\right)$$

$$E(x) = \frac{V_1}{10^{-4} \text{ cm}} = 10^4 V_1 / \text{cm}$$

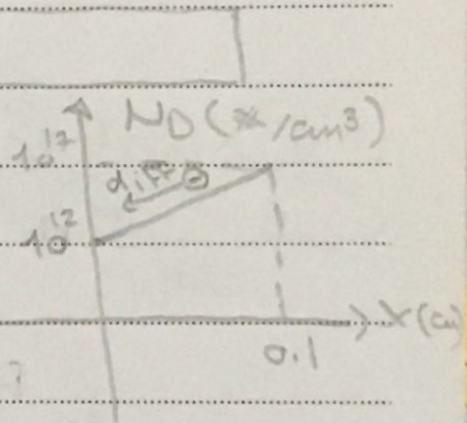
Problem 74:-

$$D_n = 22.5 \text{ cm}^2/\text{s}$$

$$D_p = 5.2 \text{ cm}^2/\text{s}$$

$$n(x) = 10^{12} + \frac{10^{17} - 10^{12}}{0.1} x$$

$$n(x) \approx 10^{12} + 10^{18} x$$



$$J_{Dn} = q D_n \nabla n = q D_n \frac{dn}{dx} = q D_n \times 10^{18}$$

$$p(x) = -\frac{n_i^2}{n(x)}$$

$$J_{Dp} = -q D_p \nabla p$$

Problem 6:-

find T such that $n_i(T) = N_A = 10^{17}/\text{cm}^3$

for Si :-

$$E_g = 1.12 \text{ eV}, N_c = 2.78 \times 10^{19} / \text{cm}^3$$

$$N_v = 9.84 \times 10^{18} / \text{cm}^3$$

نمایان کن
c.B

$$n = N_c e^{-(E_c - E_F)/k_B T}$$

$$p = N_v e^{-(E_F - E_v)/k_B T}$$

$$np = N_c N_v e^{-E_g/k_B T}$$

$$n_i^2 = N_c N_v e^{-E_g/k_B T}$$

$$n_i = \sqrt{N_c N_v} e^{-E_g/2k_B T} = N_A$$

$$T =$$

Problem 3 :-

n-type silicon

$$\rho = 5 \Omega \cdot \text{cm} \quad @ 300 \text{ K}$$

$$\mu_n(300) = 1500 \text{ cm}^2/\text{V}\cdot\text{s}$$

$$\mu_n(T) = C_1 T^{-3/2}$$

$$\rho = \frac{1}{\sigma} \Rightarrow \sigma = 0.2 / \Omega \cdot \text{cm}$$

$$\sigma_n = q n \mu_n, \quad n = N_D = \frac{\sigma_n}{q \mu_n}$$

$$\begin{aligned} \textcircled{a} \quad T = 200 \text{ K} &\Rightarrow \mu_n = C_1 T^{-3/2} \\ &\Rightarrow C_1 = \frac{\mu_n(300)}{300^{-3/2}} = \end{aligned}$$

$$\mu_n(200 \text{ K}) =$$

$$\textcircled{a} \quad T = 400 \text{ K}$$

$$\mu_n(400) =$$

Problem 11

11-240

[a]

$$f(E) = \frac{1}{1 + e^{(E-E_F)/k_B T}}$$

$$\Rightarrow 10^6 = 1 + e^{(E-E_F)/k_B T}$$

$$\frac{E-E_F}{k_B T} = 13.815$$

$$T = \frac{0.55 \times 10^{-19} \times 1.66}{13.815 \times 1.38 \times 10^{-23}}$$

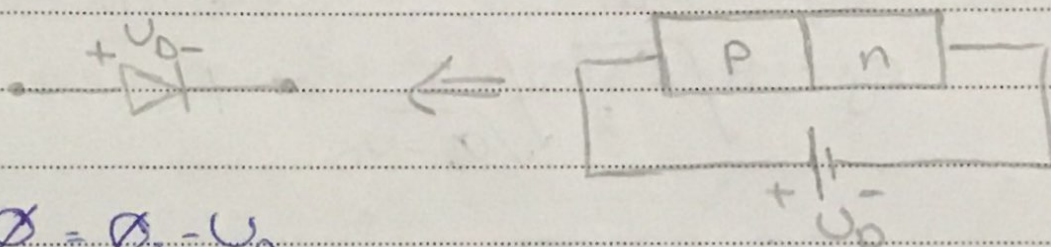
$$T \approx$$

[B]

1/4/2017

Biased p-n Junction:-

modify equation by replacing ϕ_0 by $\phi_0 - V_D$



$$\phi = \phi_0 - V_D$$

$$N_i = \frac{N_A N_D}{N_A + N_D}$$

$$E_m = \sqrt{\frac{2q N_A N_D}{\epsilon (N_A + N_D)}} \sqrt{\phi_0 - V_D}$$

$$Q_j = \sqrt{2\epsilon q N_i} \sqrt{\phi_0 - V_D}$$

$$= - \sqrt{\frac{-2q N_i}{\epsilon}} \sqrt{\phi_0 - V_D}$$

Junction capacitance:

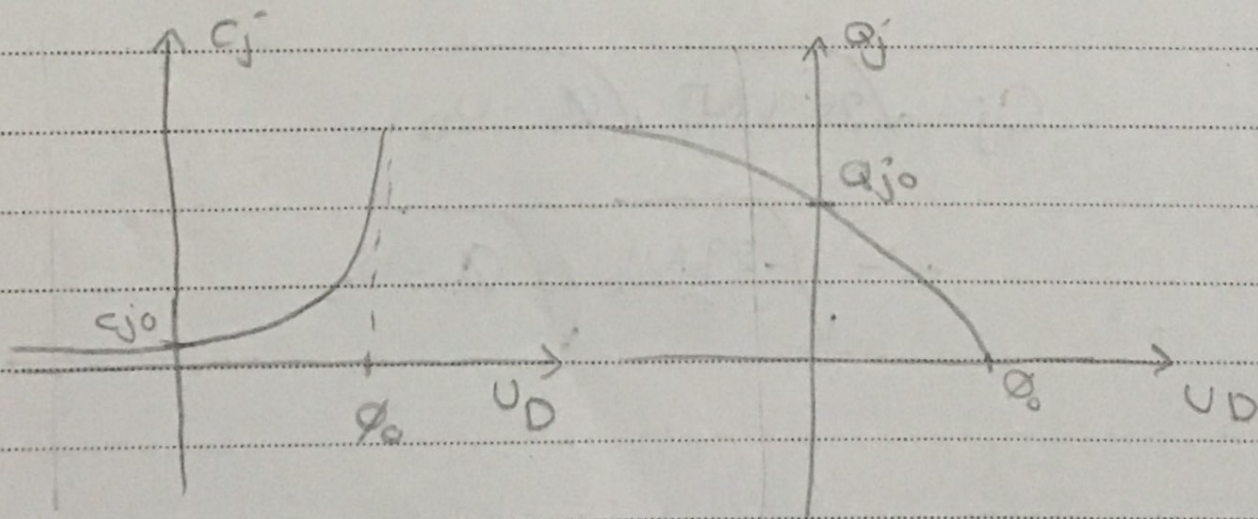
$$C_j = \frac{dQ}{d\phi}, \quad \phi = \phi_0 - V_D, \quad d\phi = -dV_D$$

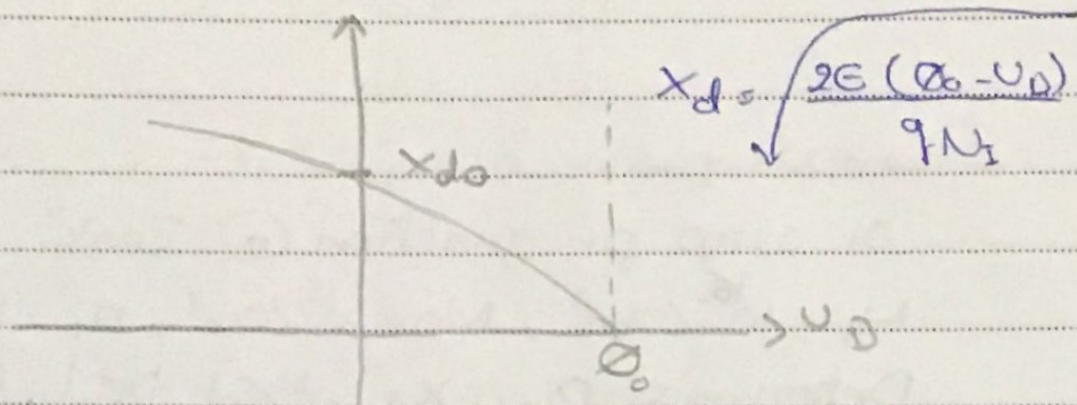
$$C_j = - \frac{dQ_j}{dV_D} = \sqrt{2\epsilon q N_A} \left(\frac{1}{\sqrt{\phi_0 - V_D}} \right) \text{ per unit area}$$

$$C_j = A \sqrt{\frac{\epsilon q N_A}{2}} \frac{1}{\sqrt{\phi_0 - V_D}}$$

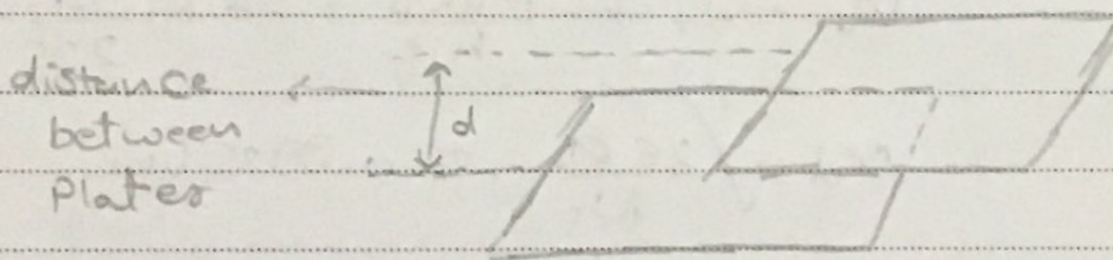
$$= \left(A \sqrt{\frac{\epsilon q N_A}{2}} \frac{1}{\sqrt{\phi_0}} \right) \frac{1}{\sqrt{1 - V_D/\phi_0}}$$

$$= \frac{C_{j0}}{\sqrt{1 - \frac{V_D}{\phi_0}}} \rightarrow \text{Junction capacitance @ no bias}$$





considering the junction capacitance as a parallel plate capacitor

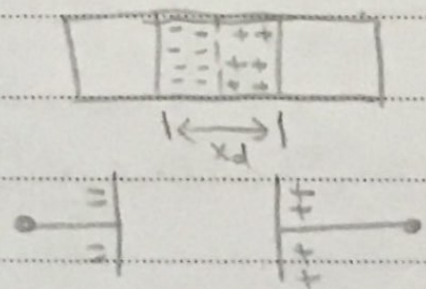


Permittivity of dielectric between plates

$$C = \frac{\epsilon A}{d}$$

cross section area

$$C_j = \frac{\epsilon A}{x_d} = \frac{\epsilon A}{\sqrt{\frac{2E(\phi_0 - V_D)}{qN_A}}}$$



$$V_d = +0.5V$$

$$dV_d = -1V$$

Example 2-

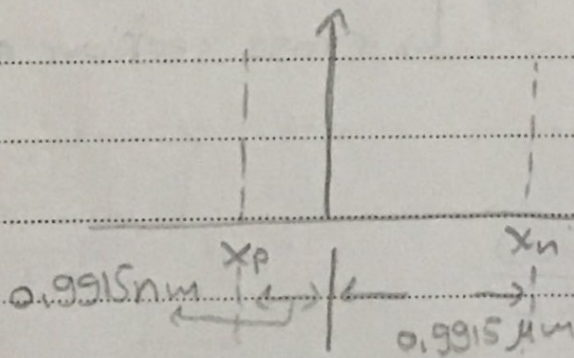
Si step pn junction @ $300K^\circ$ with
 $N_A = 10^{15}/cm^3$, $N_D = 10^{15}/cm^3$, $n_i = 1.5 \times 10^{10}/cm^3$
 Determine ϕ_0 , x_d , $|x_p|$, $|x_n|$, E_m , Q_j
 C_j @ no bias

$$V_T \approx 26 mV$$

$$\phi_0 = V_T \ln \frac{N_A N_D}{n_i^2} = 26 \ln \frac{10^{15}}{2.25} = 537 mV$$

$$x_d = \sqrt{\frac{2\epsilon \phi_0}{N_A}} \approx 0.9925 \mu m$$

$$|x_n| = 0.9915 \mu m, |x_p| = 0.9915 nm$$



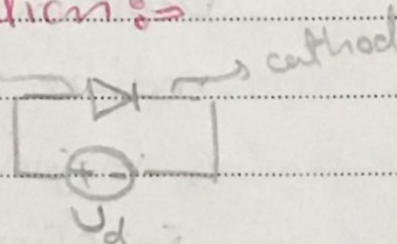
$$Q_{jo} = \sqrt{2\epsilon q N_A} \sqrt{\phi_0} = 15.8 nC/cm^2$$

$$C_{jo} = \sqrt{\frac{\epsilon q N_A}{2}} \frac{1}{\sqrt{\phi_0}} = 10.47 nF/cm^2$$

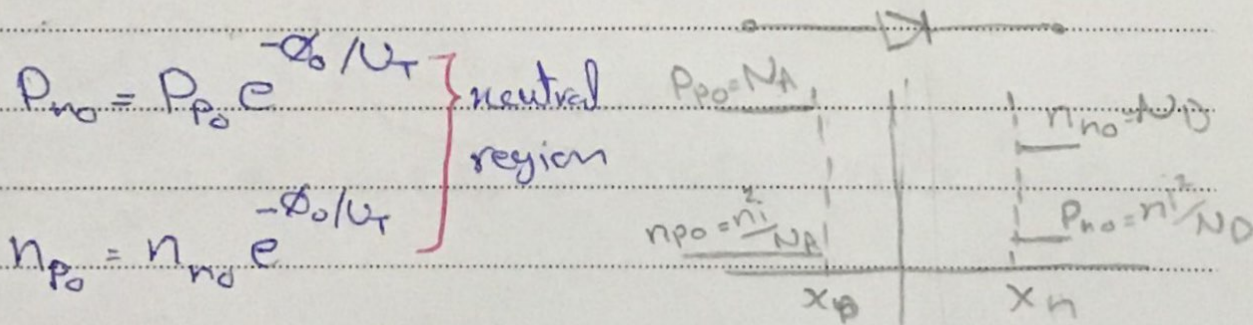
$$\epsilon_m = -1.525 \times 10^4 \text{ V/cm}$$

The Biased p-n junctions:

- A pn junction is said to be forward Bias if $V_D > 0$.
- A pn junction is said to be reverse Bias if $V_D < 0$.



for open circuit pn junction:



for $x_p \leq x \leq x_n$: $p(x) = P_p0 e^{-\phi(x)/V_T}$, $n(x) = n_n0 e^{-\phi(x)/V_T}$

for a reverse biased pn junction ($V_D < 0$):

Depletion region widens, barrier potential ϕ increases ($\phi = \phi_0 - V_D$)

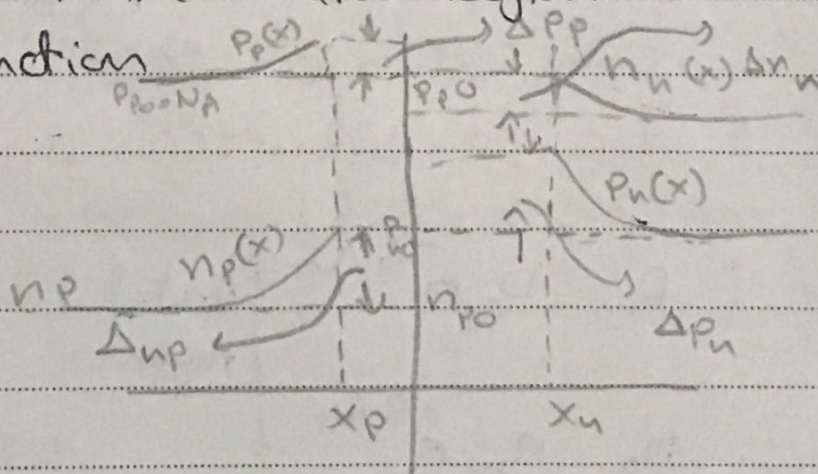
⇒ Diffusion of majority carriers because more difficult

The forward biased pn junction ($V_p > 0$)

Depletion region ^{width} shrinks, barrier potential reduce ($\phi = \phi_0 - V_p$)

⇒ majority carrier diffuse across the junction easier

⇒ concentration of minority carriers increase in the neutral region near the junction



But to maintain charge neutrality, in the neutral region, the concentration of majority must increase by the same amount

$$\Delta P_p(x) = \Delta n_p(x), \Delta n_n(x) = \Delta P_n(x)$$

$$\phi = -V_p \ln\left(\frac{P_{n0}}{P_{p0}}\right) = -V_p \ln\left(\frac{n_{p0}}{n_{n0}}\right)$$

$$P_{n0} = P_{p0} e^{-\phi_0 / V_T}, \quad n_{p0} = n_{n0} e^{-\phi_0 / V_T}$$

with applied Biased V_D

$$\phi_0 \rightarrow \phi = \phi_0 - V_D$$

$$P_n(x) = P_p(x) e^{-(\phi_0 - V_D) / V_T}, \quad n_p(x) = n_n(x) e^{-(\phi_0 - V_D) / V_T}$$

$$P_n(x_n) = P_p(x_p) e^{-(\phi_0 - V_D) / V_T}, \quad n_p(x_p) = n_n(x_n) e^{-(\phi_0 - V_D) / V_T}$$

$$\frac{P_n(x_n)}{P_{n0}} > \frac{n_n(x_n)}{n_{n0}}$$

$$\frac{n_p(x_p)}{n_{p0}} > \frac{P_p(x_p)}{P_{p0}}$$

من الابل

we assume: $P_p(x_p) \approx P_{p0}$, $n_n(x_n) \approx n_{n0}$

\Rightarrow The law of the junction:-

$$P_n(x_n) = P_{p0} e^{-(\phi_0 - V_D) / V_T} = P_{p0} e^{-\phi_0 / V_T} e^{V_D / V_T} = P_{n0} e^{V_D / V_T}$$

$$P_{n0} = P_{p0} e^{-\phi_0 / V_T}$$

any additional carrier concentration from that of neutral region away from the junction considered Excess.

$$P'_n(x) = P_n(x) - P_{n0} = \text{Excess hole concentration in the n-type @ } x$$

$$n'_n(x) = n_n(x) - n_{n0} = \text{electron}$$

$$n'_p(x) = n_p(x) - n_{p0} = \text{h- p-type}$$

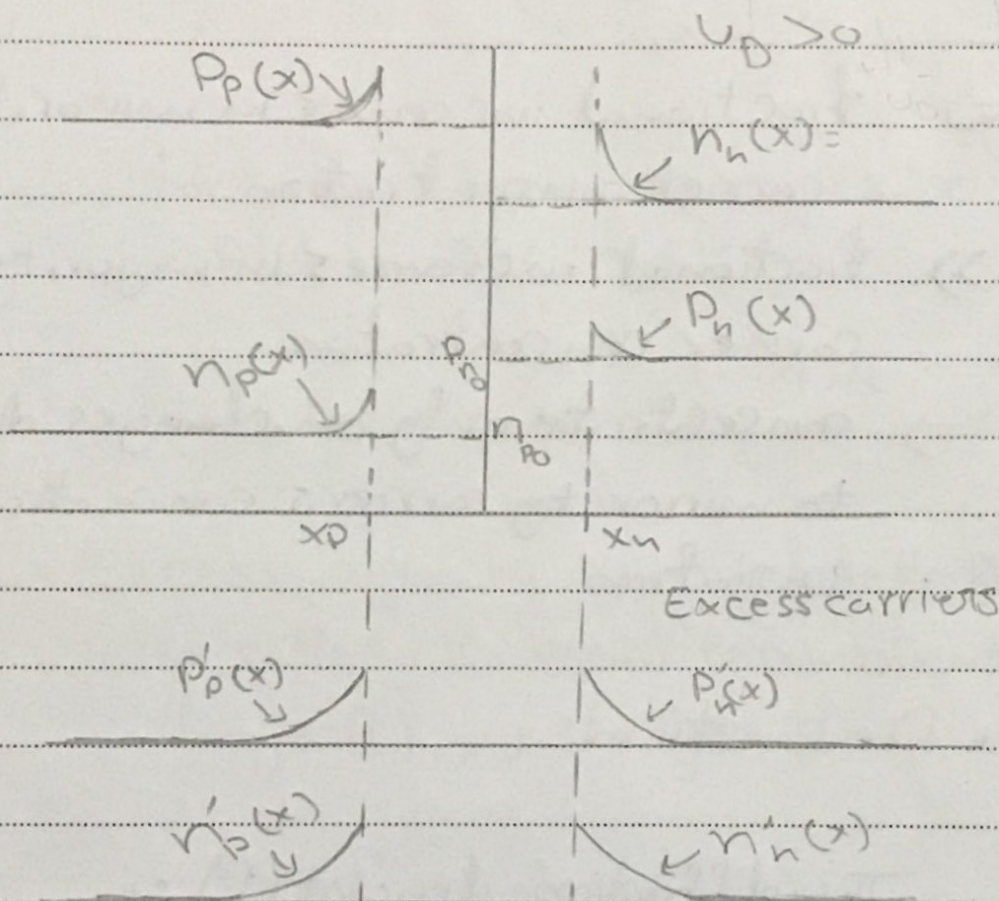
$$P'_p(x) = P_p(x) - P_{p0} = \text{holes}$$

$$P_{p0} \gg n_{p0}, n_{n0} \gg P_{n0}, P'_n(x) = n'_n(x) \\ n'_p(x) = P'_p(x)$$

$$\Rightarrow \frac{P'_n(x)}{P_{n0}} \gg \frac{n'_n(x)}{n_{n0}}, \frac{n'_p(x)}{n_{p0}} \gg \frac{P'_p(x)}{P_{p0}}$$

187 → 210
925 → 231

4/4/2017



$$P'_n(x_n) = P_n(0) e^{V_D/V_T}, \quad n'_p(x_p) = n_{p0} e^{V_D/V_T}$$

$$P'_n(x) = n'_n(x), \quad n'_p(x) = P'_p(x) \quad \leftarrow \text{to maintain charge neutrality}$$

$$P_{p0} \gg n_{p0}, \quad n_{n0} \gg P_{n0}$$

$$\frac{p'_n(x)}{p_{n0}} \gg \frac{n'_n(x)}{n_{n0}}, \quad \frac{n'_p(x)}{n_{p0}} \gg \frac{p'_p(x)}{p_{p0}}$$

\Rightarrow fractional increase in minority carrier concentration

\Rightarrow fractional increase in majority carrier concentration

* \Rightarrow concentrate only on changes due to minority carriers concentration

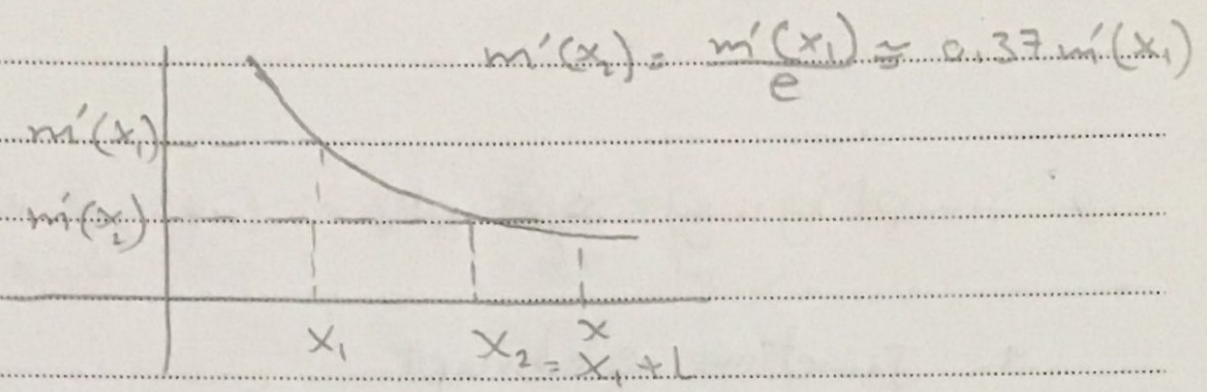
التغير - Variation

* Definitions:-

- The diffusion length (L):-

In diffusion length the concentration of minority carriers is $\frac{1}{e} \approx 0.37$ of its original value. (due to recombination)

$n'_n(x)$ = Excess minority carrier concentration



for any x : $m'(x) = m'(x_1) e^{-(x-x_1)/L}$

$\Rightarrow P'_n(x) = P'_n(x_n) e^{-(x-x_n)/L}, x > x_n > 0$

$n'_p(x) = n'_p(x_p) e^{(x-x_p)/L}, x \leq x_p < 0$

Excess minority carrier life (τ) :-

also called The mean recombination Time
longer(l) \Rightarrow longer (τ)

$$D = \frac{l^2}{\tau} \cdot \frac{cm^2}{s} \quad (m^2/s)$$

In the neutral n-region $\Rightarrow D_p = \frac{l_p^2}{\tau_p}$

" " " p-region $\Rightarrow D_n = \frac{l_n^2}{\tau_n}$

In Si typical values l_p, l_n $1 \rightarrow 100 \mu m$

&

τ_p, τ_n $10 ns \rightarrow 1 \mu s$

* Simplifying assumptions: - ^{to derive ideal diode equation}

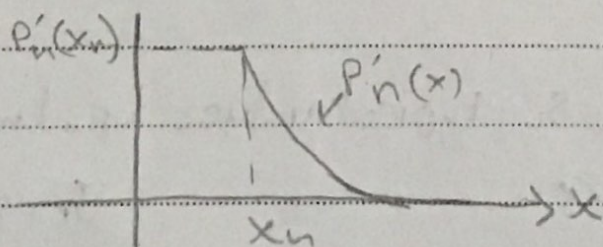
1. Junction is abrupt
2. All V_b appears across the junction
3. current flow is in one direction
4. $E = 0$ in the neutral region
5. No net generation or recombination in the Depletion Region
6. low level injection \Rightarrow concentration of minority carriers \gg concentration of majority carriers

$E = 0$ in neutral region \Rightarrow No drift current in neutral regions.

Concentration in neutral n-region:-

There is concentration gradient of Excess minority carriers

\Rightarrow There is a hole diffusion current.



$$J_p(x_n) = -q D_p \frac{dP_n(x)}{dx} \Big|_{x=x_n}$$

$$\frac{dP_n(x)}{dx} = \frac{d}{dx} [P'_n(x) + P_{n0}] = \frac{dP'_n(x)}{dx}$$

$$= \frac{d}{dx} [P'_n(x_n) e^{-(x-x_n)/L_p}] \cong \frac{d}{dx} [P'_n(x_n) e^{-x/L_p}]$$

$$x_n \cong 0$$

$$P'_n(x) = P'_n(x_n) e^{-x/L_p} = (P_n(x_n) - P_{n0}) e^{-x/L_p}$$

$$P_n(x_n) = P_{n0} e^{V_0/V_T} \Rightarrow P'_n(x) = [P_{n0} e^{V_0/V_T} - P_{n0}] e^{-x/L_p}$$

$$= P_{n0} [e^{V_0/V_T} - 1] e^{-x/L_p}$$

$$\frac{dP'_n(x)}{dx} = -\frac{P_{n0}}{L_p} (e^{V_0/V_T} - 1) e^{-x/L_p}$$

$$\frac{dP'_n(x)}{dx} \Big|_{x=x_n} = -\frac{P_{n0}}{L_p} (e^{V_0/V_T} - 1) e^0 = -\frac{P_{n0}}{L_p} (e^{V_0/V_T} - 1)$$

$$\therefore \bar{J}_p(x_n) = \frac{+qD_p P_{n0}}{L_p} (e^{V_0/V_T} - 1)$$

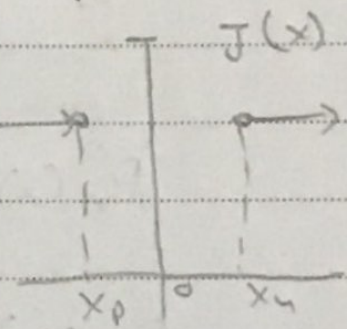
* in the neutral p-region

The electric field current density @ x_p

$$\text{in } \bar{J}_n(x_p) = \frac{qD_n n_{p0}}{L_n} (e^{V_0/V_T} - 1)$$

$$\text{Assumption (5)} \Rightarrow \bar{J}_p(x_p) = \bar{J}_p(x_n)$$

$$\bar{J}_n(x_p) = \bar{J}_n(x_n)$$



$$\begin{aligned} \bar{J}(0) &= \bar{J}_p(0) + \bar{J}_n(0) \\ &= \bar{J}_p(x_p) + \bar{J}_n(x_n) \\ &= \bar{J}_p(x_n) + \bar{J}_n(x_p) \end{aligned}$$

$$\bar{J}(0) = \frac{qD_p P_{n0}}{L_p} (e^{V_0/V_T} - 1) + \frac{qD_n n_{p0}}{L_n} (e^{V_0/V_T} - 1)$$

$$\bar{J}(0) = q \left[\frac{D_p P_{n0}}{L_p} + \frac{D_n n_{p0}}{L_n} \right] (e^{V_0/V_T} - 1)$$

$$I_0 = \bar{J}(0)A = qA \left[\frac{D_p P_{n0}}{L_p} + \frac{D_n n_{p0}}{L_n} \right] (e^{V_0/V_T} - 1)$$

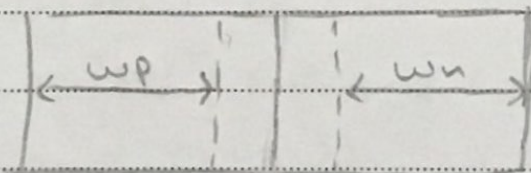
$$\Rightarrow I_s (e^{V_0/V_T} - 1)$$

$I_s \triangleq$ Reverse saturation current

$$= qA \left[\frac{D_p P_{no}}{L_p} + \frac{D_n n_{po}}{L_n} \right]$$

Actual expression for I_s (more accurate)

$$I_s = qA \left[\frac{D_p P_{no}}{L_p} \text{cath}\left(\frac{w_p}{L_p}\right) + \frac{D_n n_{po}}{L_n} \text{cath}\left(\frac{w_n}{L_n}\right) \right]$$



$$P_{no} = \frac{n_i^2}{N_D}, \quad n_{po} = \frac{n_i^2}{N_A}, \quad D = \frac{L^2}{\tau}$$

$$\therefore I_s = qA \left[\frac{L_p P_{no}}{\tau_p} \text{cath}\left(\frac{w_p}{L_p}\right) + \frac{L_n n_{po}}{\tau_n} \text{cath}\left(\frac{w_n}{L_n}\right) \right]$$

$$= qA n_i^2 \left[\frac{L_p}{\tau_p N_D} \text{cath}\left(\frac{w_p}{L_p}\right) + \frac{L_n}{\tau_n N_A} \text{cath}\left(\frac{w_n}{L_n}\right) \right]$$

Reminder :-

$$\cosh(y) = \frac{e^y + e^{-y}}{e^y - e^{-y}}$$

$\cosh \rightarrow$ الزائدية
↑
مشتق

for $y \gg 1 \Rightarrow e^y \cong 0 \cong \cosh y \cong 1$ long bias

for $y \ll 1 \Rightarrow e^y \cong 1+y, e^{-y} \cong 1-y$ short bias

no width

$$\Rightarrow \cosh(y) \cong \frac{2}{2y} = \frac{1}{y}$$

* long bias diode ($w \gg L$)

$$\Rightarrow \cosh(y) \cong 1$$

$$I_s = qA \left[\frac{D_p p_{n0}}{L_p} + \frac{D_n n_{p0}}{L_n} \right]$$

* short bias diode :-

$$w \ll L \Rightarrow \cosh\left(\frac{w}{L}\right) \cong \frac{L}{w}$$

* * $\Rightarrow I_s = qA \left[\frac{D_p p_{n0}}{w_n} + \frac{D_n n_{p0}}{w_p} \right]$

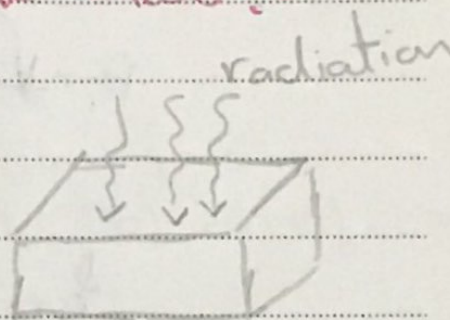
Tutorial

* solution of homework Two:-

$$Q5) N_D - N_A = 10^{16} / \text{cm}^2$$

after exposure

$$P_{no} = 10^{13} / \text{cm}^3$$



before exposure:-

$$P_{no} = \frac{n_i^2}{N_D} = \frac{2.25 \times 10^{20}}{10^{16}} = 2.25 \times 10^4$$

$$P + N_D = n + N_A, \quad np = n_i^2$$

$$\frac{n_i^2}{n} + N_D = n + N_A$$

$$n_i^2 + nN_D = n^2 + nN_A$$

$$n^2 + n(N_A - N_D) - n_i^2 = 0$$

$$n = \frac{(N_D - N_A) + \sqrt{(N_A - N_D)^2 + 4n_i^2}}{2}$$

$$p = \frac{\sqrt{(N_A - N_D)^2 + 4n_i^2} - (N_A - N_D)}{2}$$

for n-type material

$$N_A = 0 \Rightarrow n = \frac{N_D + \sqrt{N_D^2 + 4n_i^2}}{2} = N_D$$

for p-type material

$$N_D = 0 \Rightarrow n = N_A$$

$$p_{no} = \frac{n_i^2}{N_D} \Rightarrow n_i = \sqrt{N_D p_{no}}$$

Q3

$$\phi_0 = U_T \ln \frac{NA ND}{n_i^2}$$

$$n_i = n_i(290K)$$

find T such $\phi_0(T) = \phi_0(290) - 0.04\phi_0(290)$

$$d\phi_0 = -0.04\phi_0(290)dT$$

$$\frac{d\phi_0}{dT} = -0.04\phi_0(290)$$

$$\frac{d\phi_0}{dT} = \frac{\phi_0 - U_g}{T} + \frac{dU_g}{dT} - \frac{3k}{q}$$

$$E_g = q U_g = 0.67 \text{ eV} \Rightarrow U_g = \frac{0.67}{1e} = 0.67$$

$$\frac{dE_g}{dT} = 0 \Rightarrow \frac{dU_g}{dT}$$

$$\frac{d\phi_0}{dT} = \frac{\phi_0 - 0.67}{290} - x$$

$$\frac{-0.04\phi_0}{dT} = \frac{\phi_0 - 0.67}{290} - x$$

Q2) all $\phi_0 = V_T \ln \frac{N_A N_D}{(n_i)^2}$

$$n_i = K_1 T^{3/2} e^{-E_g/2kT}$$

$$\frac{d\phi_0}{dT} = V_T \frac{d}{dT} \left[\ln \frac{N_A N_D}{(n_i)^2} + \ln \frac{N_A N_D}{(n_i)^2} \right] \frac{dT}{dT}$$

$$\frac{dV_T}{dT} = \frac{d}{dT} \left[\frac{k_B T}{q} \right] = \frac{k_B}{q} = \frac{V_T}{T}$$

$$\ln x = \frac{1}{x}$$

$$\ln y = \frac{1}{y} \frac{dy}{dx} \rightarrow \frac{d}{dT} \left[\ln \frac{N_A N_D}{(n_i)^2} \right] = \frac{n_i^2}{N_A N_D} \frac{d}{dT} \frac{N_A N_D}{(n_i)^2}$$

$$\frac{d}{dT} \left(\frac{N_A N_D}{n_i^2} \right)$$

$$\frac{dx}{dT} = \frac{dx}{dn_i} \frac{dn_i}{dT}$$

$$\frac{dx}{dn_i} = \frac{d}{dn_i} (N_A N_D n_i^{-2}) = -\frac{2 N_A N_D}{n_i^3}$$

$$\frac{dn_i}{dT} = \underbrace{k_1 T^{\frac{3}{2}} e^{-E_g / k_B T}}_{n_i} \frac{d}{dT} \left(\frac{-E_g}{k_B T} \right)$$

$$\frac{d}{dT} \left(\frac{-E_g}{k_B T} \right) = -\frac{d}{dT} \left(\frac{q U_g}{k_B T} \right)$$

$$= -\frac{q}{k_B} \frac{d}{dT} \left(\frac{U_g}{T} \right) = -\frac{q}{k_B} \left(\frac{T \frac{dU_g}{dT} - U_g}{T^2} \right)$$

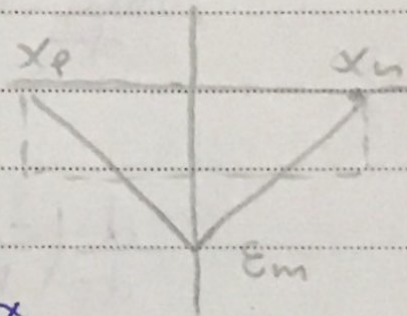
$$\frac{dx}{dT} = + \frac{2 N_D N_A}{n_i^3} \frac{q}{k_B} \left(\frac{T \frac{dU_g}{dT} - U_g}{T^2} \right)$$

$$\frac{d}{dT} \left(\ln \frac{N_A N_D}{n_i^2} \right) = \frac{n_i^2}{N_A N_D} \times \frac{2 N_D N_A q}{n_i^3 k_B} \left(\frac{T \frac{dU_g}{dT} - U_g}{T^2} \right)$$

$$= \frac{29 n_i^2}{k_B T^2} \left(T \frac{dU_g}{dT} - U_g \right)$$

من هذا يمكن انفس القدره
سها

Q4) a//



$$\bar{E}_m = \frac{1}{x_d} \int_{x_p}^{x_n} E(x) dx$$

$$= \left[\frac{1}{2} x_d E_m \right] \times \frac{1}{x_d}$$

$$\Rightarrow = \frac{1}{2} E_m$$

8/4/2017

Q2) a-

Show that $\frac{d\phi}{dT} = \frac{\phi_0 - U_g}{T} + \frac{dU_g}{dT} - \frac{3k_B}{q}$

$\phi_0 + U_g \ln \frac{N_A N_D}{(n_i)^2}$, $n_i = K_1 T^{\frac{3}{2}} e^{-E_g/2k_B T}$

$\frac{d\phi_0}{dT} = \ln \left[\frac{N_A N_D}{(n_i)^2} \right] \frac{dU_g}{dT} + U_g \frac{d}{dT} \left[\ln \frac{N_A N_D}{(n_i)^2} \right]$

$\ln \left[\frac{N_A N_D}{(n_i)^2} \right] = \ln N_A N_D - 2 \ln n_i$

$\frac{dU_g}{dT} = \frac{k_B}{q} = \frac{U_g}{T}$

$\Rightarrow \frac{d}{dT} \ln \left(\frac{N_A N_D}{n_i^2} \right) = \frac{-2}{n_i} \frac{dn_i}{dT}$

$\frac{d}{dT} \ln \left(\frac{N_A N_D}{(n_i)^2} \right) = \frac{(n_i)^2}{N_A N_D} \frac{d}{dT} \left[\frac{N_A N_D}{(n_i)^2} \right]$

$= \frac{(n_i)^2}{N_A N_D} \left[\frac{-2 N_A N_D n_i}{n_i^4} \right] \frac{dn_i}{dT} = \frac{-2}{n_i} \frac{dn_i}{dT}$

$$\frac{dn_i}{dT} = \frac{3}{2} k_B \frac{1}{T} e^{\frac{-E_g}{2k_B T}} + k_B T^{\frac{3}{2}} e^{\frac{-E_g}{2k_B T}} \frac{d}{dT} \left(\frac{-E_g}{2k_B T} \right)$$

$$= \frac{3/2 n_i}{T} + n_i \frac{d}{dT} \left(\frac{-E_g}{2k_B T} \right) = n_i \left[\frac{3/2}{T} - \frac{d}{dT} \left(\frac{E_g}{2k_B T} \right) \right]$$

$$\frac{d}{dT} \left(\frac{E_g}{2k_B T} \right) = \frac{2k_B T \frac{dE_g}{dT} - 2k_B E_g}{4k_B^2 T^2}$$

$$= \frac{T \frac{dE_g}{dT} - E_g}{2k_B T^2}$$

$$E_g = q U_g \Rightarrow \frac{dE_g}{dT} = q \frac{dU_g}{dT}$$

$$\Rightarrow \frac{d}{dT} \left(\frac{E_g}{2k_B T} \right) = \frac{q T \frac{dU_g}{dT} - q U_g}{2k_B T^2}$$

$$= \frac{q \left(T \frac{dU_g}{dT} - U_g \right)}{2k_B T^2}$$

$$\Rightarrow \frac{d}{dT} \ln \frac{N_{AND}}{n_i^2} = \frac{-2}{n_i} n_i \left[\frac{3/2}{T} - \frac{q(T \frac{du_g}{dT} - U_g)}{2k_B T^2} \right]$$

$$= \frac{-2}{T} \left[3/2 - \frac{q(T \frac{du_g}{dT} - U_g)}{2k_B T} \right]$$

$$\Rightarrow \frac{d\phi_o}{dT} = \frac{U_T}{T} \ln \frac{N_{AND}}{(n_i)^2} - \frac{2U_T}{T} \left[3/2 - \frac{q(T \frac{du_g}{dT} - U_g)}{2k_B T} \right]$$

$$= \frac{\phi_o}{T} - \frac{k_B T}{qT} \left[3 - \frac{q(T \frac{du_g}{dT} - U_g)}{k_B T} \right]$$

$$= \frac{\phi_o}{T} - \left[\frac{3k_B}{q} - \frac{T \frac{du_g}{dT} - U_g}{dT} \right]$$

$$\frac{d\phi_o}{dT} = \frac{\phi_o - U_g}{T} + \frac{du_g}{dT} - \frac{3k_B T}{q}$$

$$\Rightarrow \frac{d}{dT} \ln \frac{N_{AND}}{n_i^2} = \frac{-2}{n_i} n_i \left[\frac{3/2}{T} - \frac{q(T \frac{du_g}{dT} - U_g)}{2k_B T^2} \right]$$

$$= \frac{-2}{T} \left[3/2 - \frac{q(T \frac{du_g}{dT} - U_g)}{2k_B T} \right]$$

$$\Rightarrow \frac{d\phi_o}{dT} = \frac{U_T}{T} \ln \frac{N_{AND}}{(n_i)^2} - \frac{2U_T}{T} \left[3/2 - \frac{q(T \frac{du_g}{dT} - U_g)}{2k_B T} \right]$$

$$= \frac{\phi_o}{T} - \frac{k_B T}{qT} \left[3 - \frac{q(T \frac{du_g}{dT} - U_g)}{k_B T} \right]$$

$$= \frac{\phi_o}{T} - \left[\frac{3k_B}{q} - \frac{T \frac{du_g}{dT} - U_g}{dT} \right]$$

$$\frac{d\phi_o}{dT} = \frac{\phi_o - U_g}{T} + \frac{du_g}{dT} - \frac{3k_B T}{q}$$

تقل زیادہ ہو جائے

b// $N_D = 10^{14} / \text{cm}^3$, $N_A = 10^{18} / \text{cm}^3$

calculate $\frac{d\phi_0}{dT}$ @ 305°K & ϕ_0

$$\phi_0(305^\circ\text{K}) = \phi_0(300^\circ\text{K}) + d\phi_0|_{T=300^\circ\text{K}}$$

$$\phi_0(300^\circ\text{K}) = V_T \ln \frac{N_A N_D}{(N_i)^2} \approx 25 \ln \frac{10^{32}}{2.25 \times 10^{20}} \text{ mV}$$

$$= 447 \text{ mV}$$

$$\left. \frac{d\phi_0}{dT} \right|_{300^\circ\text{K}} = \left[\frac{\phi_0(300^\circ\text{K}) - V_g}{T} + \frac{dV_g}{dT} - \frac{3k_B}{eV} \right] dT$$

$$\left. \frac{d\phi_0}{dT} \right|_{300^\circ\text{K}} = \frac{447 - 1120}{300} - 0.275 - \frac{3 \times 1.38 \times 10^{-23}}{1.6 \times 10^{-19}}$$

$\Delta T \times 5 \leftarrow$

$$\phi_0(305^\circ) = 434.5 \text{ mV}$$

Q10

Given: $\phi_0 = 447 \text{ mV}$, $\frac{d\phi_0}{dT} = -2.5 \text{ mV/K}$ @ 300

find T @ which $\phi_0 = 460 \text{ mV}$

or simply $\frac{d\phi_0}{dT} = 2.5 \text{ mV/K}$, $d\phi_0 = 13$

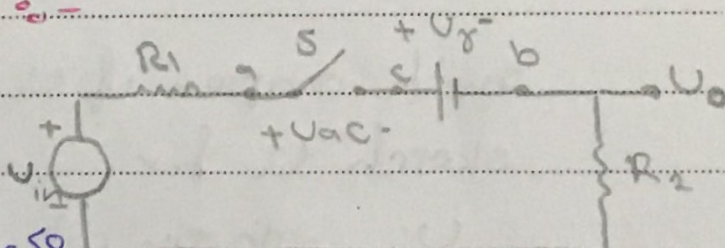
$$dT = \frac{13}{-2.5} \Rightarrow T = 294.8 \text{ K}$$

Problem set zero:-

switch S remains

open as long as $U_{AC} > 0$

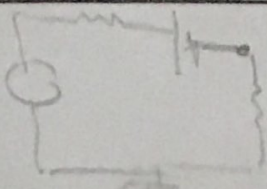
Sketch U_0 as function in U_{in}



when switch S open $U_0 = 0$

because $U_0 = U_{R2} = IR = 0$

when switch S closed $\Rightarrow U_0 = \left(\frac{R_2}{R_1 + R_2} \right) U_{in}$



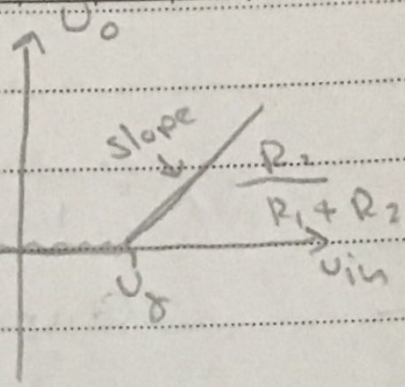
Subject:

S is open $\Rightarrow U_0 < 0$

when S is open

$$U_{AC} = U_A - U_C$$

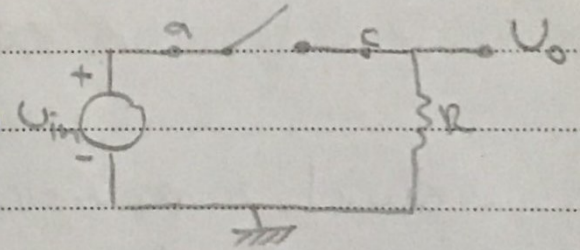
$$= U_{in} - U_2$$


$$S$$
 is open if $U_n - U_g < 0$

2, 1, 2, 0 in UV_8

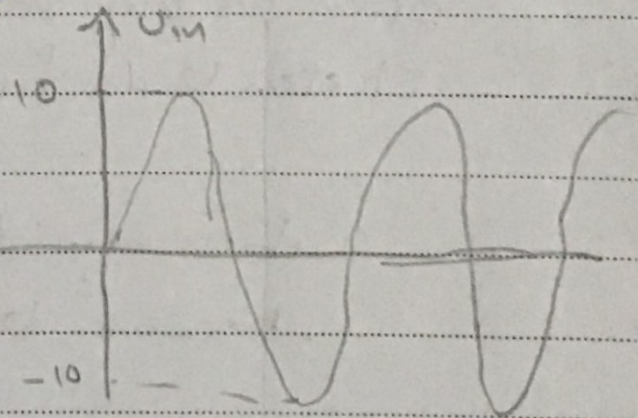
s is closed for $U_{in} \geq U_x$

switch is open if U_{act}
sketch U_0 for

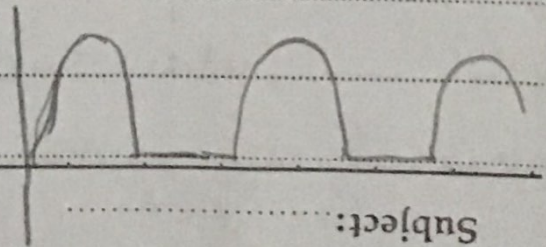


$$V_{in} = 10 \sin \omega t \text{ V}$$

$$V_o = \begin{cases} 0 & \text{for } V_{in} < 0 \\ V_{in} & \text{for } V_{in} \geq 0 \end{cases}$$

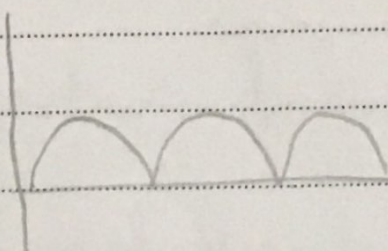


The circuit is called
Half wave Rectifier
(HWR)



Subject:

full wave Rectifier

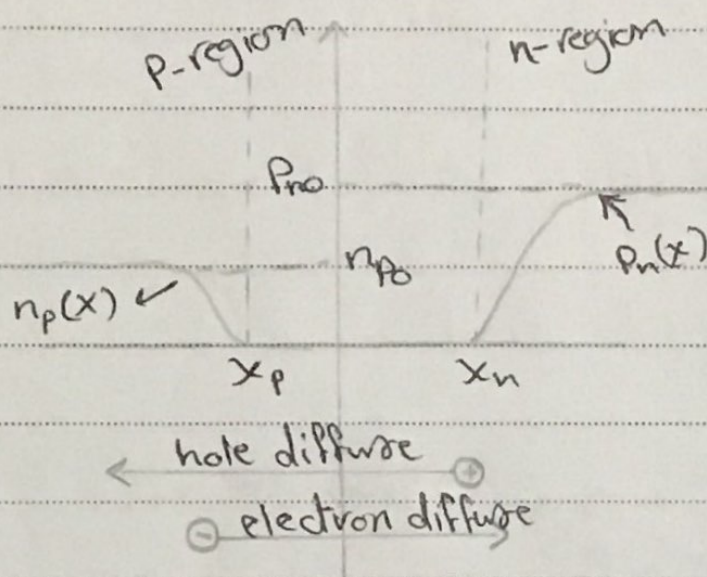


$$V_o = |V_{in}|$$

Test one #

11/4/2017

The reverse biased p-n junction:-



from the law of the junction:-

$$P_n(x_n) = P_{p0} e^{V_D/V_T}$$

for reverse bias

$$V_D < 0 :-$$

$$\text{for } |V_D| \ll T$$

$$P_n(x_n) \cong 0$$

$$n_p(x_p) \cong 0$$

- from concentration gradient of minority carrier.

⇒ +ve current flows from n-region to p-region.

$|I_D|, |I_{D0}|$

$$(I_D < 0)$$

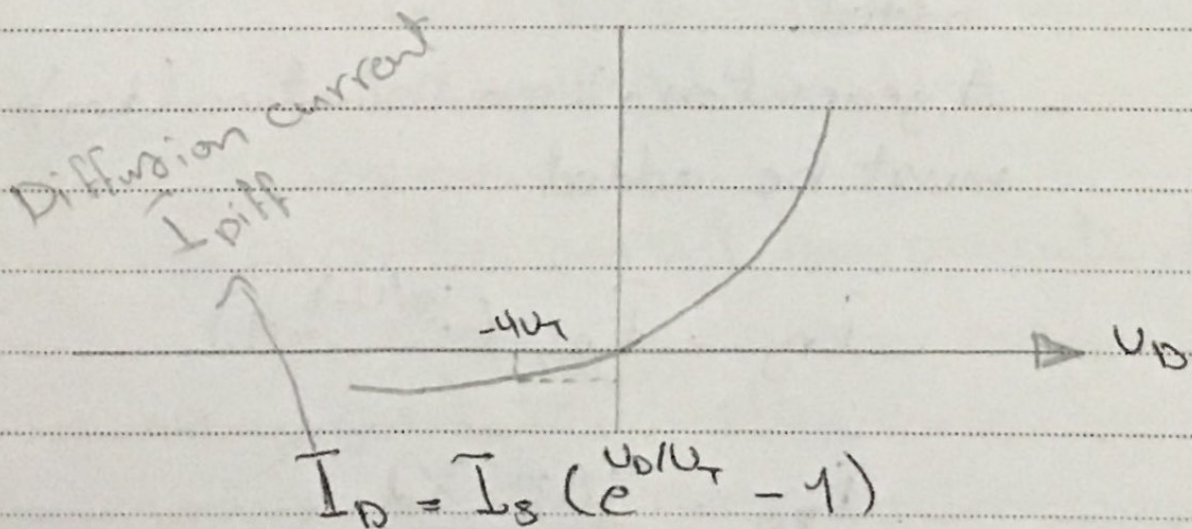
I_D is very small

for $|V_D| \ll 4V_T$ ($V_D \ll -4V_T$):-

$$e^{V_D/4V_T} \ll e^{-1} \approx 0$$

⇒ concentration gradient doesn't change very much in slope

⇒ diffusion current saturate



for $(V_D < -4V_T) \Rightarrow I_D < I_S(e^4 - 1) \approx I_S$

اعتباراته

Practical considerations:-

1. measured values of I_D with reverse biased is much greater than computes by the formula $|I_D| \gg |I_S|$

2. under forward biased ... of the carriers injected in the depletion region recombine ^{بالتالي} given rise ^{التي} a recombination current that must be added.

under reverse biased injected in The depletion region give rise to ^{بالتالي} generation current that must be added.

A generation - Recombination (I_{rg}) must be added

$$I_{rg} = I_{R0} (e^{V_D/4V_T} - 1)$$

$$I_{R0} = \frac{q A n_i x_d}{2 \tau_0}$$

$\tau_o = \tau_{po} = \tau_{no}$ effective life time
of carrier in the depletion
region

for $V_D < -4V_T$

$$\Rightarrow \bar{I}_{ng} \approx -I_{R0}$$

$$\Rightarrow \bar{I}_D = \bar{I}_{diff} + \bar{I}_{ng}$$

$$\Rightarrow \bar{I}_D = I_0 (e^{V_D/4V_T} - 1) + \bar{I}_{R0} (e^{V_D/2V_T} - 1)$$

- for a reverse biased p-n junction
($8V_D < -4V_T$)

3. There is surface leakage current
($\sim 1 \text{ nA}$) should be added

are one

* since \uparrow the current components dominates
the other

$$\Rightarrow \bar{I}_D = \bar{I}_0 (e^{V_D/4V_T} - 1)$$

if $I_{\text{diff}} \gg I_{\text{rg}} \Rightarrow I_0 = I_s$ & $\eta = 1$

if $I_{\text{rg}} \gg I_{\text{diff}} \Rightarrow I_0 = I_{\text{ro}}$ & $\eta = 2$

- Notes:-

① $I_s \propto n_i^2$, $I_{\text{ro}} \propto n_i$

② $\frac{V_0}{V_T} \gg \frac{V_0}{2V_T}$ for $V_0 > 0.1$

③ n_i for Ge is much larger than n_i for Si & GaAs

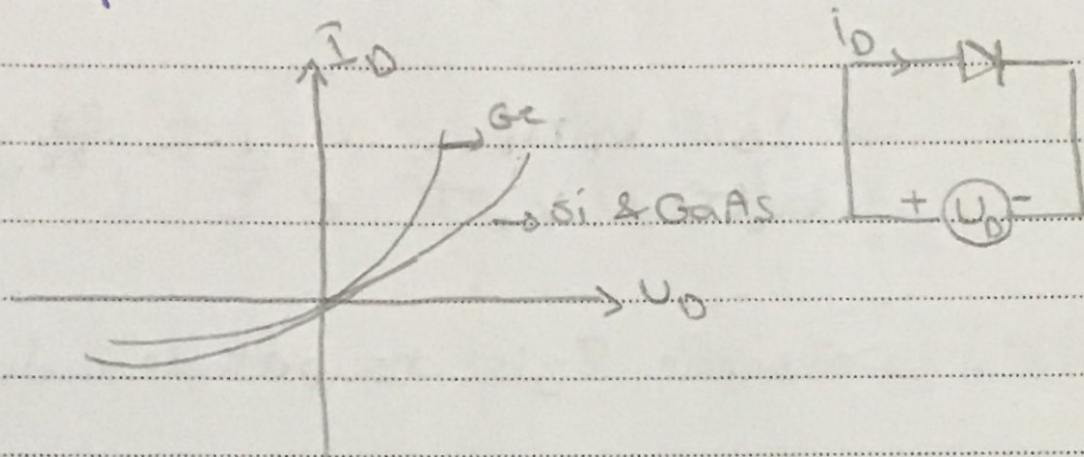
④ n_i increases with temperature

$\Rightarrow I_s \gg I_{\text{ro}}$ @ high temperature
even if n_i is small

$\Rightarrow I_{\text{rg}} \gg I_s$ @ very low temperature
even if n_i is large

- In most cases ($I_{\text{diff}} \gg I_{\text{rg}}$) except
for Si & GaAs @ low temperature
& reverse biased and for Ge @ low

temperature & small for reverse biased



with reverse biased a very small $(-I_D)$ current I_D flows

⇒ Diode allows current to flow in only one direction

* Temperature effect:-

$$I_D = I_0 \left(e^{U_D / \eta U_T} - 1 \right)$$

① $I_0 = I_s$ or I_{s0} , $I_s \propto n_i^2$, $I_{s0} \propto n_i$
(n_i) increase with temperature

② The Thermal voltage ($U_T = \frac{k_B T}{q}$) linearly increases with Temperature

Dependence of I_s on T :-

$$I_s = k_1 n_i^2$$

$$n_i(T) = k_2 T^{\frac{3}{2}} e^{-\frac{E_g}{2k_B T}}$$

Assume E_g is temperature independent

$$\frac{dI_s}{dT} = 2k_1 n_i \frac{dn_i}{dT}$$

$$\frac{dn_i}{dT} = \frac{3}{2} k_2 T^{\frac{1}{2}} e^{-\frac{\alpha}{T}} - \alpha k_2 T^{\frac{3}{2}} e^{-\frac{\alpha}{T}} \frac{d}{dT} \frac{1}{T}$$

$$= 2k_1 n_i \left[\frac{3/2 n_i}{T} + \frac{\alpha n_i}{T^2} \right]$$

$$= 2 \frac{k_1 n_i^2}{T} \left[\frac{3}{2} + \frac{\alpha}{T} \right] = \frac{2I_s}{T} \left[\frac{3}{2} + \frac{\alpha}{T} \right]$$

$$\frac{dI_s/dT}{I_s} = \frac{1}{T} \left[3 + \frac{2\alpha}{T} \right]$$

$$\textcircled{a} \quad 300\text{K} \Rightarrow \frac{dI_s/dT}{I_s} = \begin{cases} \frac{1}{300} \left[3 + \frac{1400}{300} \right] \\ \approx 0.16 \text{ for Si} \\ \frac{1}{3} \left[3 + \frac{1900}{300} \right] \\ \approx 0.11 \text{ for Ge} \end{cases}$$

what is ΔT that makes I_s doubles?!

$$\text{for Ge } (0.11)^{\Delta T} = 2$$

$$\Delta T = \ln\left(\frac{2}{0.11}\right) \approx 7^\circ$$

$$\text{for Si } (0.16)^{\Delta T} = 2$$

$$\Delta T = \ln\left(\frac{2}{0.16}\right) = 5^\circ\text{C}$$

↓
Practical (8°)

11/4/2017

مسألة

* Temperature coefficient of I_D for fixed V_D :-

- for a forward biased diode :-

$$I_D = I_s (e^{V_D/V_T} - 1) \approx e^{V_D/V_T} \cdot I_s$$

$$\left[\frac{dI_D/dT}{I_D} \right] = \frac{1}{I_D} \frac{d}{dT} [I_s e^{V_D/V_T}]$$

$$= \frac{1}{I_D} \left[\frac{dI_s}{dT} e^{V_D/V_T} + I_s \frac{d}{dT} e^{V_D/V_T} \right]$$

$$= \frac{e^{V_D/V_T}}{I_D} \frac{dI_s}{dT} + \frac{I_s}{I_D} \left[e^{V_D/V_T} \frac{d}{dT} \left(\frac{V_D}{V_T} \right) \right]$$

$$V_T = \frac{k_B T}{q}$$

The continue of lecture
is after the next lecture
"after the lecture of Date 29/4"
when u will study u should
follow the original sequence

29/4/2017

* Application of Diode (Diode circuit):-
Diode is nonlinear ckt element

$$I_D = I_S (e^{V_D/V_T} - 1)$$

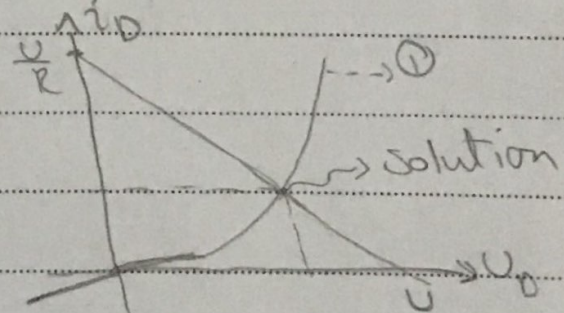
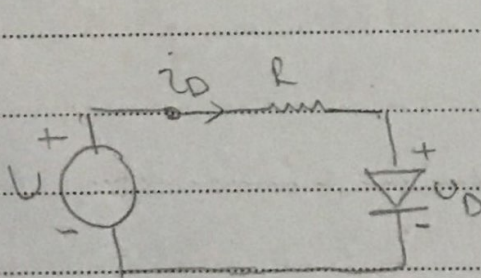
=> Exact solution requires solving nonlinear eqns

- practically, you can estimate approximate solution, by modeling the Diode as a piece wise linear ckt element.

I) Exact solution (Example):-

For the Diode: $i_D = I_S (e^{V_D/V_T} - 1) \rightarrow (1)$

load line eqn $i_D = \frac{V - V_D}{R} \rightarrow (2)$



Newton's methods to solve non linear
solution:- eqn

find x for which $f(x) = 0$

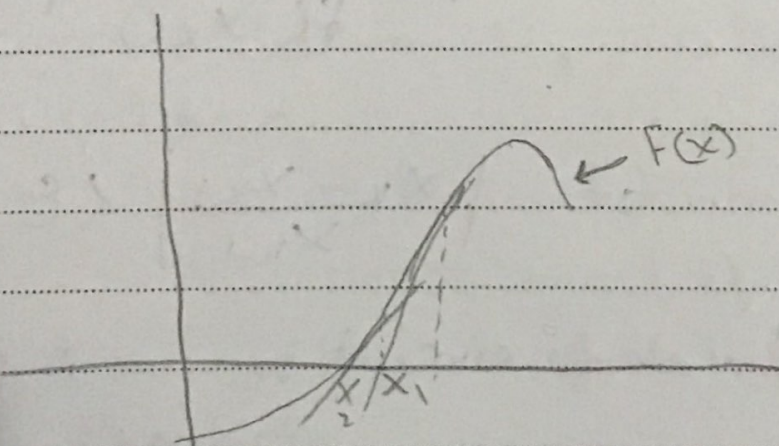
Expansion of $f(x)$ about x_0

$$f(x) = \sum_{n=0}^{\infty} \frac{(x-x_0)^n}{n!} f^{(n)}(x_0)$$

$$= f(x_0) + (x-x_0) f'(x_0) + \frac{(x-x_0)^2}{2} f''(x_0) + \dots$$

Assume $f(x)$ is linear in region very close to x_0

$$\Rightarrow f(x) \approx \frac{f(x_0) + (x-x_0) f'(x_0)}{g(x)}$$



$$f(x) = f(x_0) - (x - x_0) f'(x_0) = 0$$

$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)}$$

$$x_2 = x_1 - \frac{f(x_1)}{f'(x_1)}$$

* Algorithm :-

① initial guess x_0

② Iterate the

$$x_k = x_{k-1} - \frac{f(x_{k-1})}{f'(x_{k-1})}, k=1, 2, 3$$

③ stop if $\left| \frac{f(x_k) - f(x_{k-1})}{f(x_{k-1})} \right| < \epsilon$ [$\epsilon = 1 \times 10^{-6}$]

$$\text{or } \left| \frac{x_k - x_{k-1}}{x_{k-1}} \right| < \epsilon$$

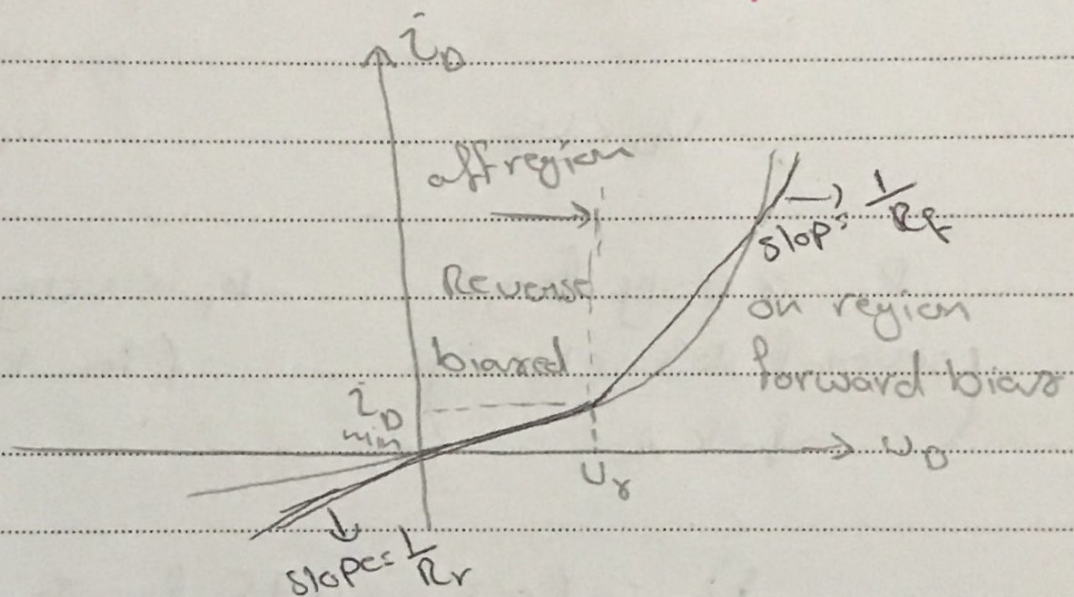
* For the diode circuit :-

$$f(V_D) = (1) - (2)$$

$$f(V_D) = I_S (e^{V_D/V_T} - 1) - \frac{V - V_D}{R}$$

$$I'(V_D) = \frac{I_s e^{V_D/V_T}}{V_T} + \frac{1}{R}$$

* Piece-wise linear model of diode :-

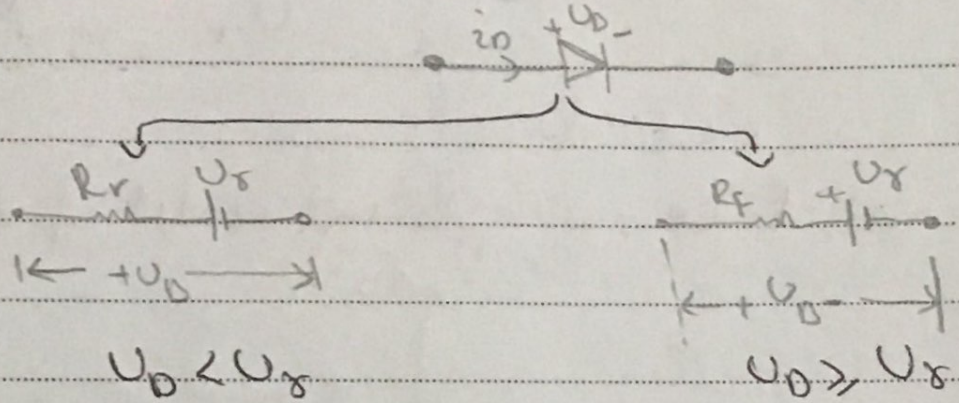


- assume diode is on if a minimum forward current $I_{D \min}$. V_g is called the cut-in voltage.

i.e Diode is forward biased if $V_D > V_g$
& reverse biased if $V_D < V_g$

- for $V_D < V_g$, approximate the charact

model one :-



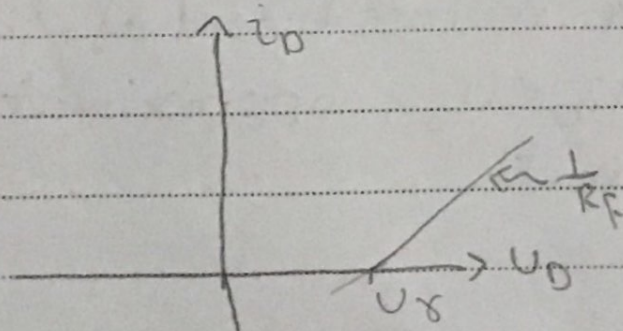
R_r is very large
(several 10's or 100's
of $k\Omega$)

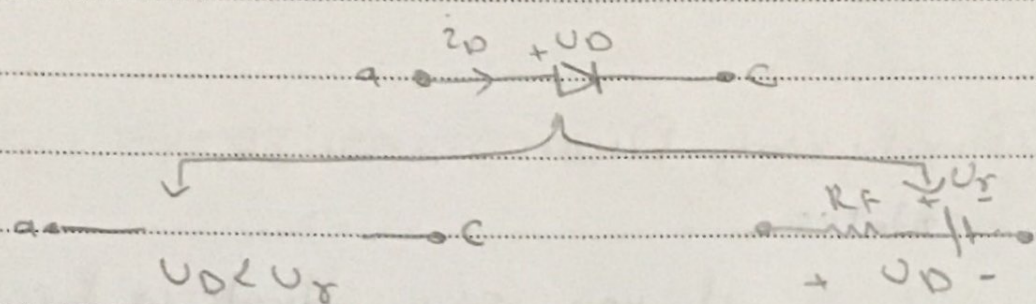
R_f is very small
(few 10's of Ω)

V_r : (0.5 → 0.75 for Si diodes)
: (0.15 → 0.25 for Ge diodes)

model Two :-

R_r is large (assume $R_r = \infty$)





Analyzing Diode Circuits :-

Notes -

- if you assume diode is forward biased you must get $i_D \geq 0$
- if you assume diode is reverse biased, you must get $V_D < V_D$

Example :-

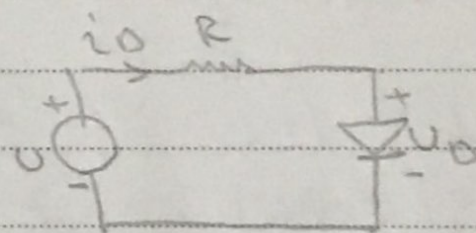
Determine i_D , V_D

$$R = 10\text{ k}\Omega, V_D = 0.7\text{ V}$$

$$R_F = 0.1\text{ k}\Omega, R_R = \infty$$

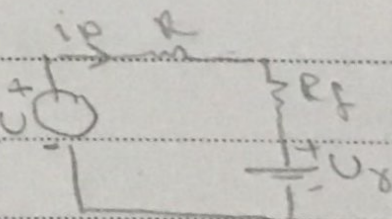
for a // $V = 0.2\text{ V}$

b // $V = 5\text{ V}$



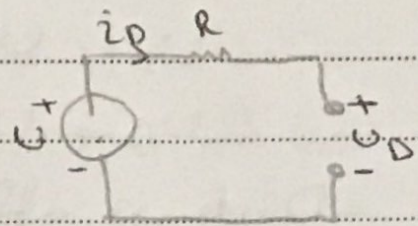
a// assume diode is forward biased

$$i_D = \frac{V - V_D}{R + R_F} = \frac{0.2 - 0.7}{10.1} = \frac{-0.5}{10.1}$$



the assumption is wrong Diode is off

$$i_D = 0 \Rightarrow U_D = U = 0.2 \text{ V}$$



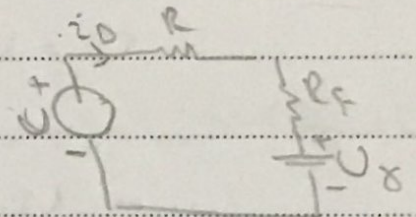
b// Assume diode is off.

$$i_D = 0 \Rightarrow U_D = U = 5 \text{ V}$$

$\Rightarrow U_D > U_F$ assumption is wrong

\Rightarrow Diode is on

$$i_D = \frac{U - U_F}{R + R_F} = \frac{5 - 0.7}{10.1} = 4.3 \text{ mA}$$



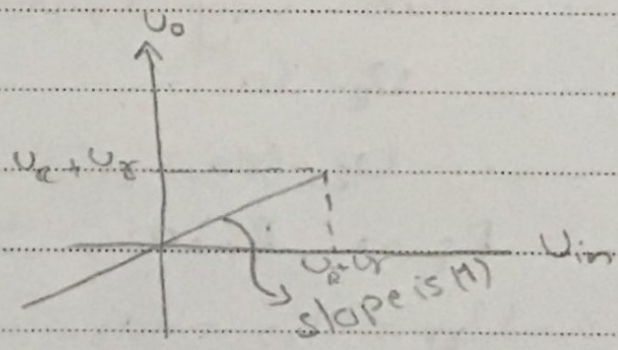
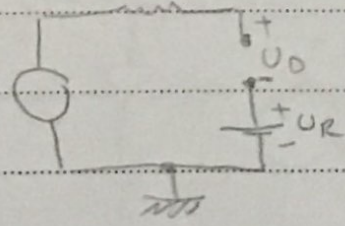
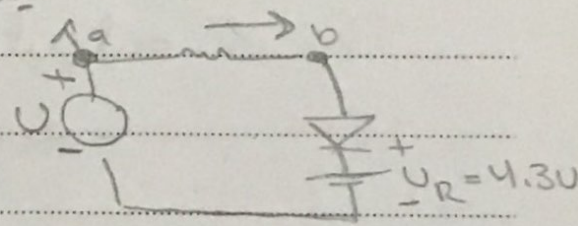
Example:-
(clipping circuit)

$$U_F = 0.7, R_F = 0, R_r = \infty$$

sketch U_o reverse U_{in}

when diode is off

diode is forward
b is a voltage divider



$$V_o = V_{in}$$

$$V_o = V_{in} - V_R$$

Diode is off as long as $V_o < V_R$

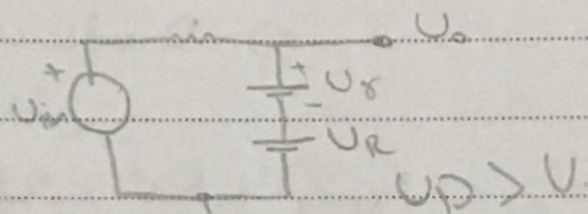
$$\Rightarrow V_{in} - V_R < V_R$$

$$\Rightarrow V_R + V_R > V_{in} \quad (V < 5V)$$

$$V_o = V \quad \text{for } V_{in} < 5$$

for $V_{in} > (V_R + V_R)$, Diode is on

$$V = V_R + V_R$$



$$V_o = \begin{cases} V_{in} & \text{for } V_{in} \leq V_R + V_R \quad (\text{forward}) \\ V_R + V_R & \text{for } V_{in} > V_R + V_R \quad (\text{reverse}) \end{cases}$$

old

output is clipped @ $V_o = V_R + V_R$

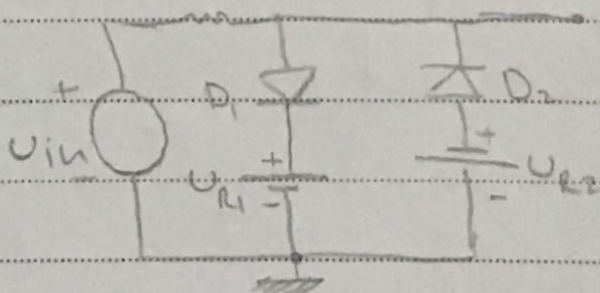
Two-way clipper :-

$$V_{R1} > 0$$

$$V_{R2} > 0$$

$$R_F = 0, R_R = \infty$$

$$V_{R1} = V_{R2} = V_R$$



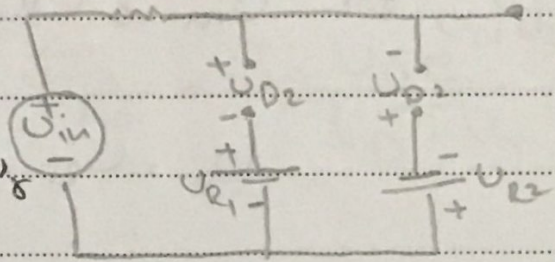
متغير شدن در خروجی لازم. لان نفس طرح لازم
 یکن آبرض U_{R1} و اقل U_{R2} و هم الزور
 متساویین - تناقض ای حاله مستقیم

when both diodes are off

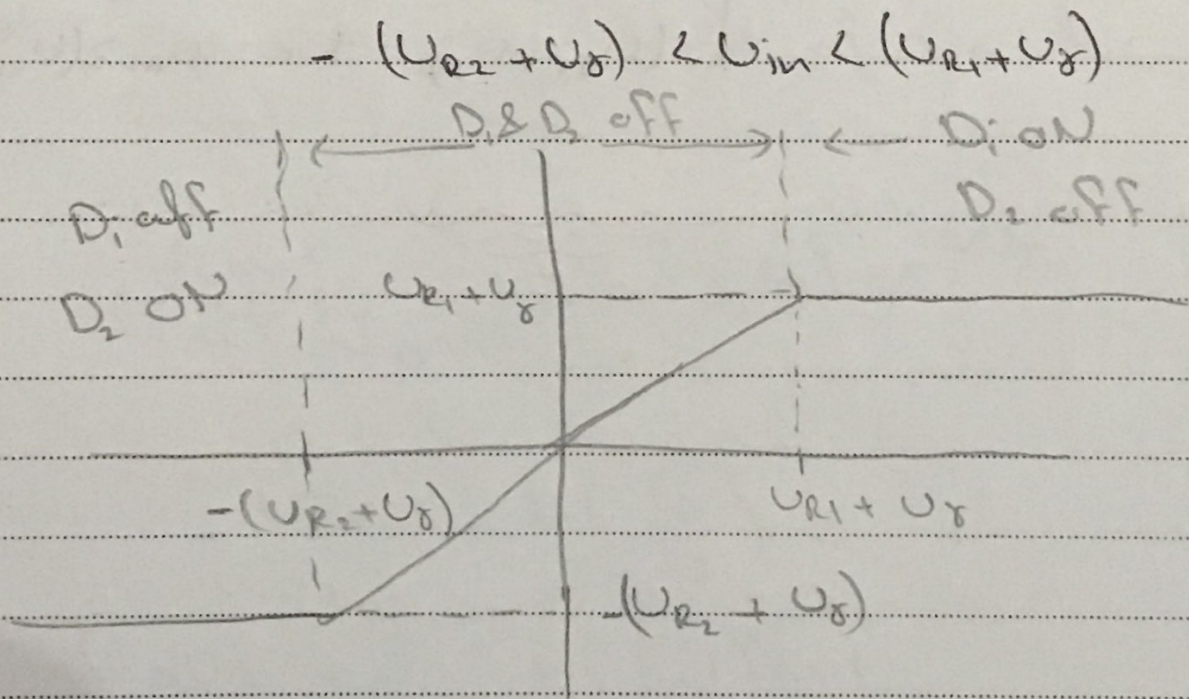
$$U_o = U_{in}$$

$$U_{D1} = U_o - U_{R1} = U_{in} - U_{R1} < U_s$$

$$\Rightarrow U_{in} < U_{R2} + U_s$$

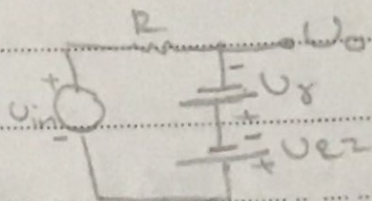


$$U_{D2} = -U_{R2} - U_o = -U_{R2} - U_{in} < U_s \Rightarrow U_{in} > -(U_{R2} + U_s)$$



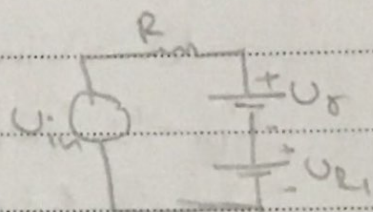
- for $V_{in} \leq -(V_{D2} + V_{D1})$, D_1 off, D_2 on

$$V_o = -(V_{D2} + V_{D1})$$

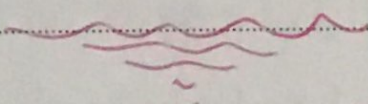


- for $V_{in} > (V_{D1} + V_{D2}) \Rightarrow D_1$ on, D_2 off

$$V_o = V_{D1} + V_{D2}$$



$$V_o = \begin{cases} -(V_{D2} + V_{D1}) & \text{for } V_{in} \leq -(V_{D2} + V_{D1}) \\ V_{in} & \text{for } -(V_{D2} + V_{D1}) < V_{in} < (V_{D1} + V_{D2}) \\ (V_{D1} + V_{D2}) & \text{for } V_{in} \geq (V_{D1} + V_{D2}) \end{cases}$$



11/4/2017

* The continue of lecture 11/4/2017

$$V_T = \frac{k_B T}{q}$$

$$\frac{d}{dT} \left(\frac{V_D}{V_T} \right) = \frac{-V_D dV_T/dT}{V_T^2} = \frac{-V_D V_T / T}{V_T^2} = \frac{-V_D}{T V_T}$$

$$\frac{dI_D/dT}{I_D} = \frac{e^{V_D/V_T}}{I_D} \frac{dI_S}{dT} = \frac{I_S V_D e^{V_D/V_T}}{I_D T V_T}$$

$$= \frac{1}{I_S} \frac{dI_S}{dT} - \frac{V_D}{T V_T} \quad *$$

* Temperature coefficient of V_D for fixed I_D :-

$$\left. \frac{dV_D}{dT} \right|_{\Delta I_D = 0}, \quad I_D \approx I_S e^{V_D/V_T}$$

$$V_D = V_T \ln \left(\frac{I_D}{I_S} \right)$$

$$\frac{dV_D}{dT} = \frac{d}{dT} \left[V_T \ln \left(\frac{I_D}{I_S} \right) \right]$$

$$= \frac{dV_T}{dT} \ln \frac{I_D}{I_S} + V_T \frac{d}{dT} \ln \left(\frac{I_D}{I_S} \right)$$

$$= \frac{V_T}{T} \ln \frac{I_D}{I_S} + V_T \frac{I_S}{I_D} \frac{d}{dT} \left(\frac{I_D}{I_S} \right)$$

$$= \frac{V_D}{T} + \frac{V_T I_S}{I_D} \left(\frac{-I_D dI_S/dT}{I_S^2} \right)$$

$$\Rightarrow \frac{dV_D}{dT} = \frac{V_D}{T} - \frac{V_T}{I_S} \frac{dI_S}{dT}$$

$$= \frac{V_D}{T} - V_T \left(\frac{dI_S/dT}{I_S} \right) *$$

Example:-

assume I_D is constant & $V_D = 0.7V$

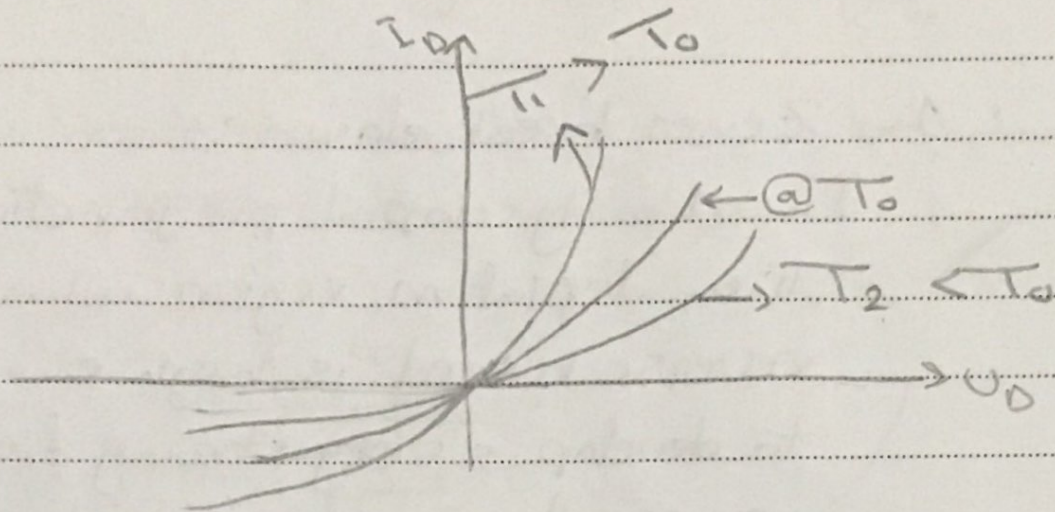
@ $300^\circ K$

for si $\frac{dI_S/dT}{I_S} \cong 0.16$

$$\frac{dV_D}{dT} = \frac{700}{300} - 25 \times 0.16 = \frac{7}{3} - 4 \text{ mV/K}$$

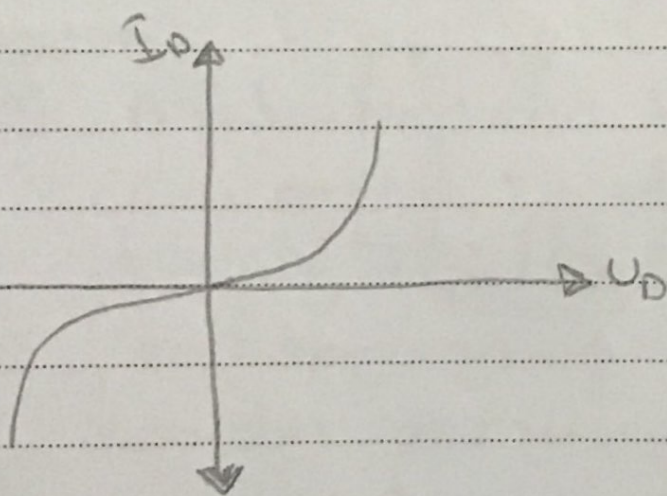
measured $\frac{dV_D}{dT}$ @ $I_D = 1 \text{ mA}$ is found

to be $\sim -2mU/k^\circ$

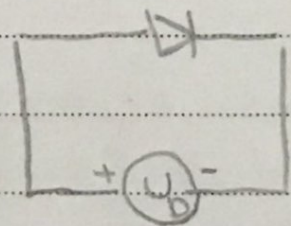


— Breakdown diode :-

Break down is electrical (Not mechanical)
(i.e. No damage)



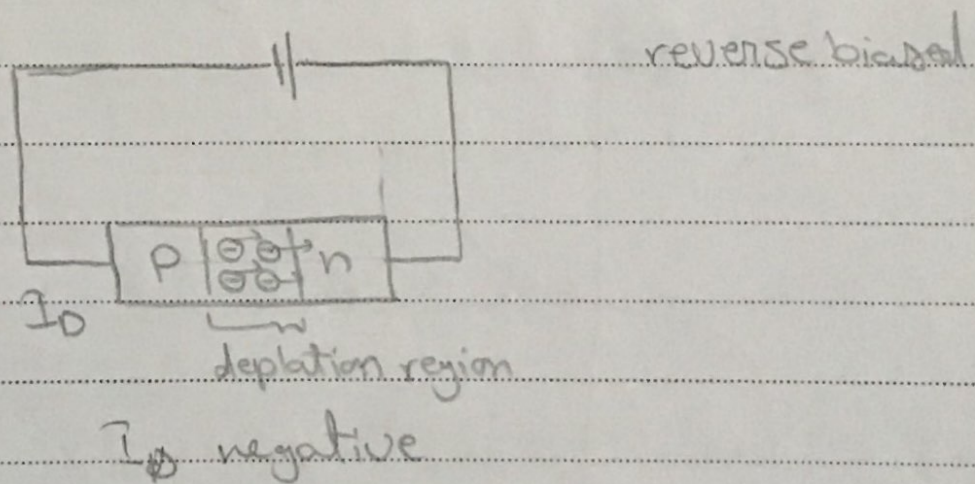
forward biased



- Break down mechanism (Two):-

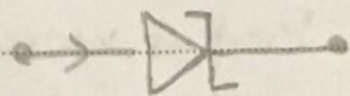
1- Zener break down:-

In a heavily doped pn junction the depletion region when the reverse biased is high enough to develop a very strong field across the junction which excites electrons from the valance band within the junction to the conduction band.

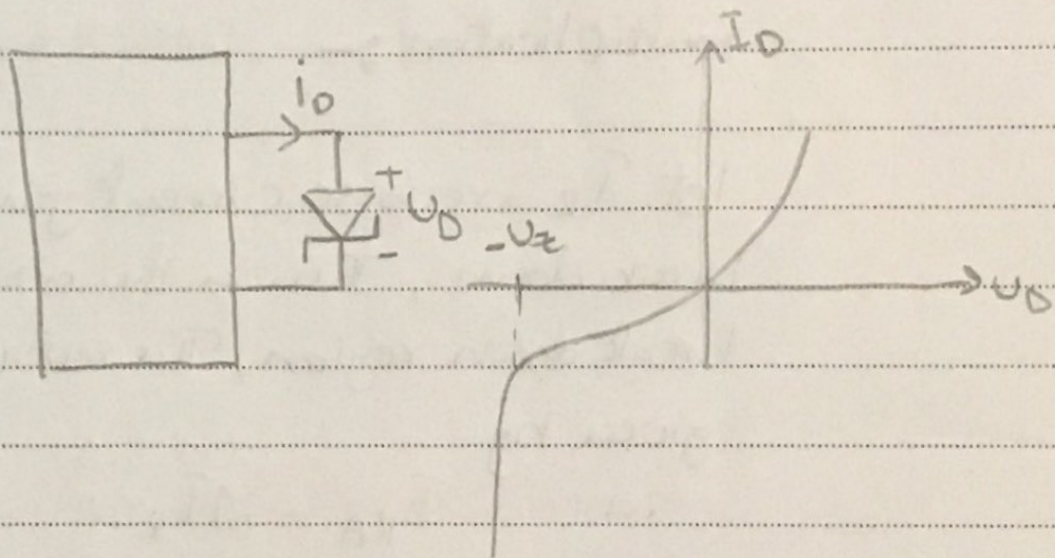


Zener break down occurs at $E_{max} \geq 10^6 \text{ V/cm}$ and doping in the range of $10^{18} / \text{cm}^3$

Zener diode symbol



break down voltage $V_Z \Rightarrow$ breakdown occurs if $V_0 \leq -V_Z$



②. A avalanche break down:-

when reverse biased is increase in a not heavily doped p-n junction [Thick depletion region] until The field E_{max} reaches $2 \times 10^5 \text{ V/cm}$. Then carriers have sufficient energy in colliding with other atoms in the depletion region producing new electron-hole pairs. The secondary carriers in turn

Produce more carriers leaving the depletion region [doping level $\sim 10^{16} / \text{cm}^3$]

* Empirical formula for avalanche multiplication :-

Let I_R = reverse current just before break down, Then in the avalanche break down region, The reverse current given by

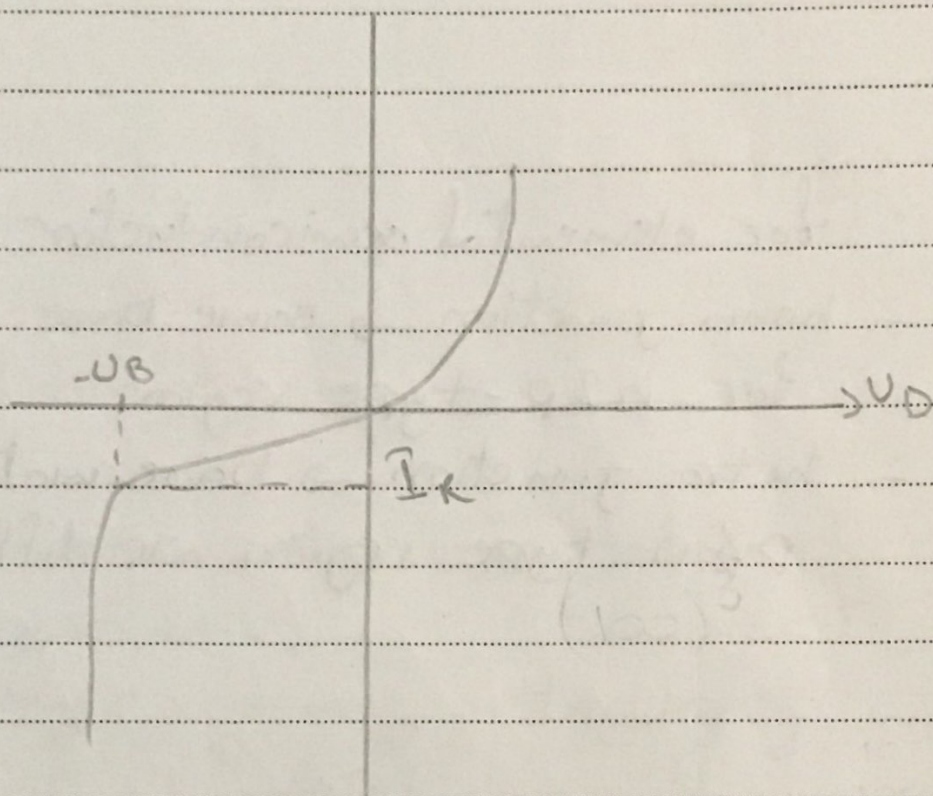
$$I_{RA} = M I_R$$

M = multiplication factor

$$M = \frac{1}{\left(1 - \left(\frac{U_R}{U_B}\right)^n\right)}$$

$U_R \rightarrow$ reverse biased

$n_i: 3 \rightarrow 6$



Approximate expression for U_B (Break down voltage) for step p-n junction

$$U_B (\text{Volts}) \cong G_0 \left[\frac{E_g}{1.1} \right]^{\frac{3}{2}} \left[\frac{N_I}{10^{16}} \right]^{\frac{3}{4}}$$

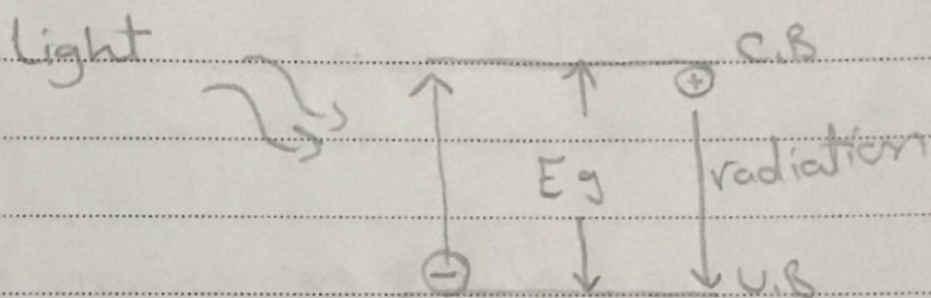
E_g in eV

$U_B > 200$
silicon

$$N_I = \frac{N_A N_D}{N_A + N_D}$$

for elemental semiconductor

- homo junction \rightarrow same base material for n & p-type region
- hetero junction \rightarrow base material p & n type region are different



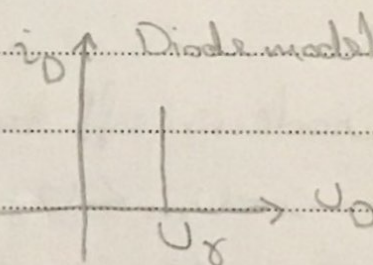
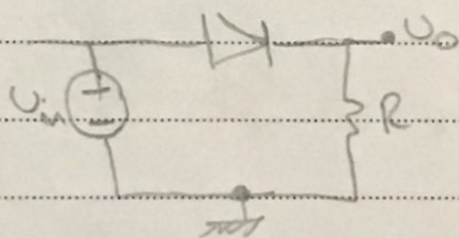
reminder read lecture
with date 29/4/2017
before this -

2/5/2017

Rectifier ckt:-

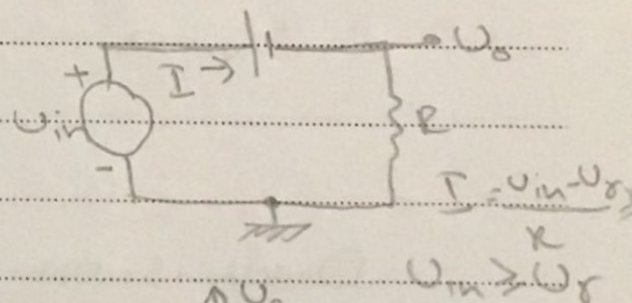
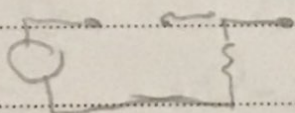
V_{in} can be +ve & $V_{in}(t)$ Rectifier $V_o(t)$
-ve when as V_o
is either +ve only or -ve only
 $\Rightarrow V_o(t) = \pm |V_{in}(t)|$

— half wave Rectifier (Hwf):-



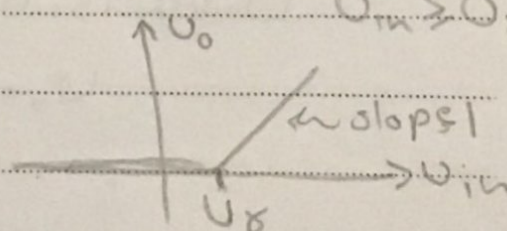
Diode off if $V_{in} < V_g$

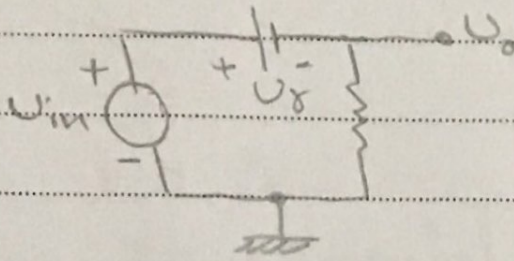
$$V_o(t) = 0$$



Diode is on if $V_{in} \geq V_g$

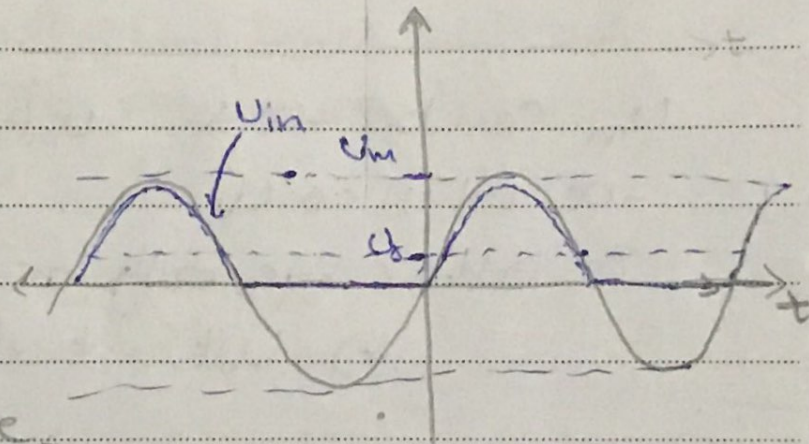
$$V_o = V_{in} - V_g$$





$$v_{out}(t) = \begin{cases} 0 & \text{if } v_{in} < U_g \\ v_{in} - U_g & \text{if } v_{in} \geq U_g \end{cases}$$

$$v_{in} = U_m \sin \omega t$$



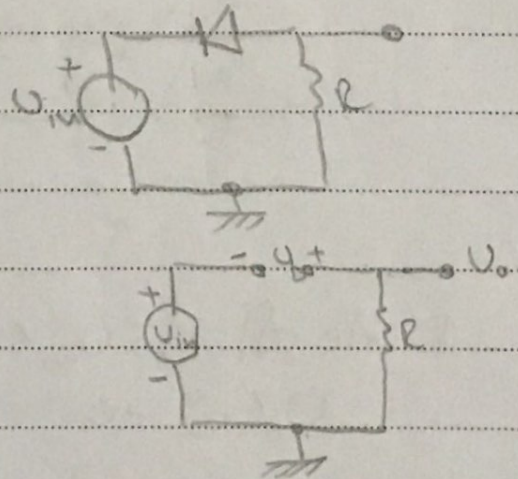
on the case

Diode is off for $v_{in} < U_g$

$$\Rightarrow -v_{in} < U_g$$

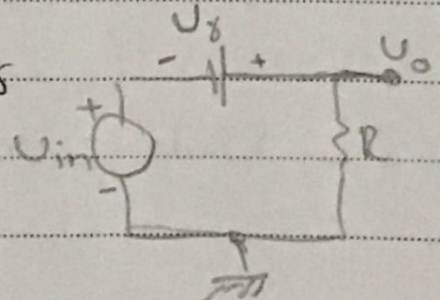
$$\Rightarrow v_{in} > -U_g$$

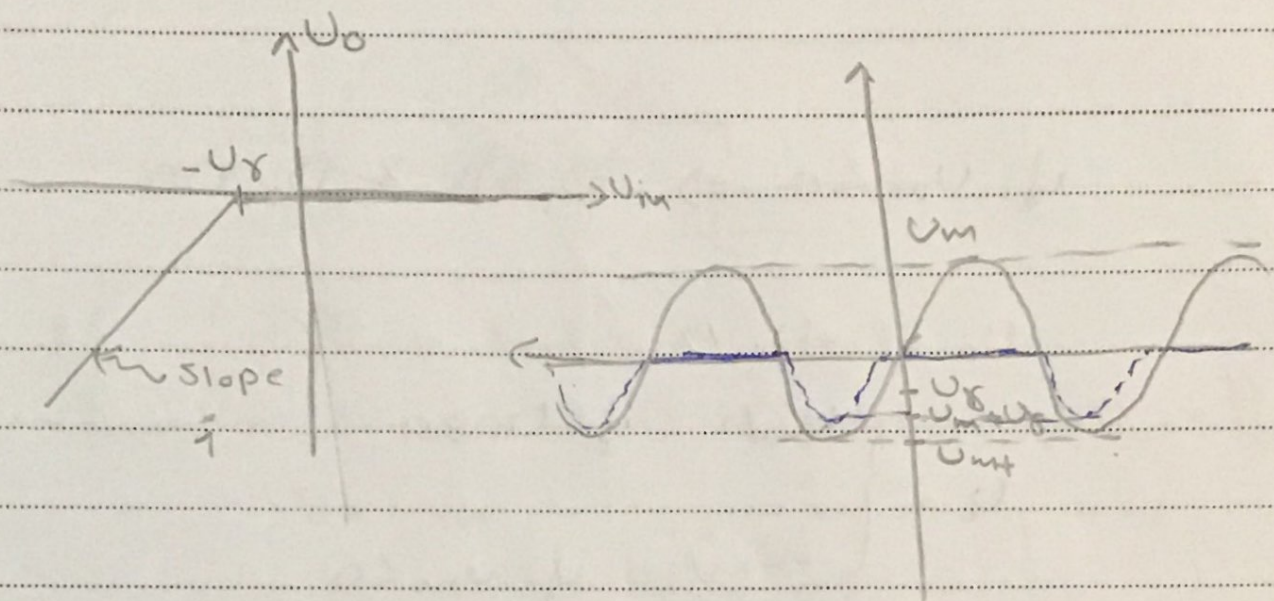
$$v_o = 0$$



Diode is on for $v_{in} \leq -U_g$

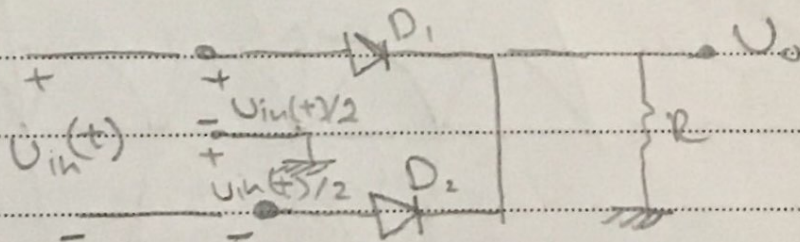
$$v_o = v_{in} + U_g$$





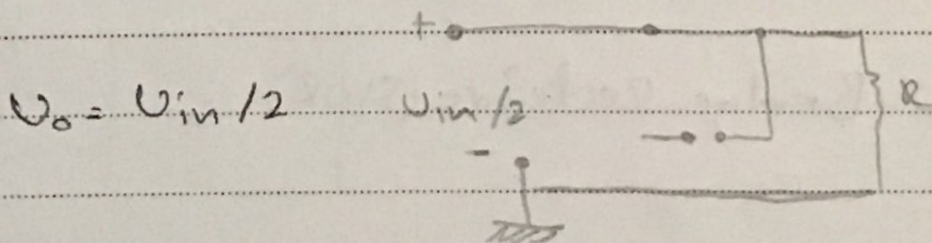
- Full wave Rectifier (FWR) :-

$$U_{in} \rightarrow \boxed{\text{FWR}} \rightarrow U_o(t) = \pm \alpha |U_{in}(t)|$$



assume diodes are ideal ($R_f = 0$, $U_g = 0$, $R_r = 0$)

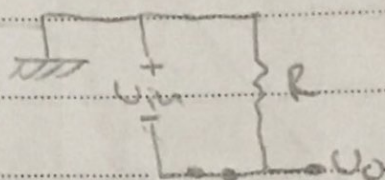
if $U_{in} > 0 \Rightarrow D_2$ is off & D_1 is on



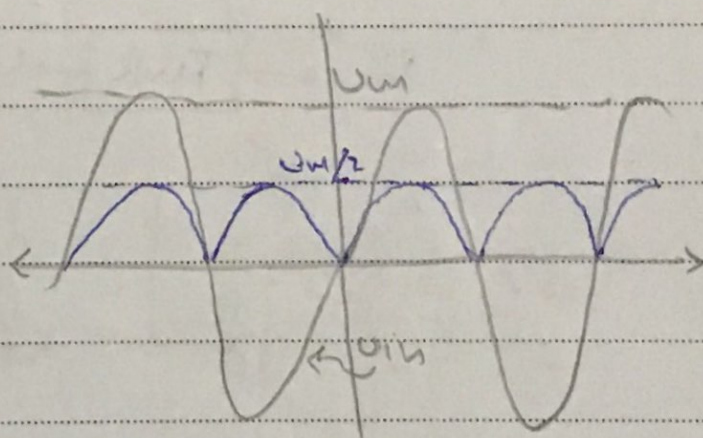
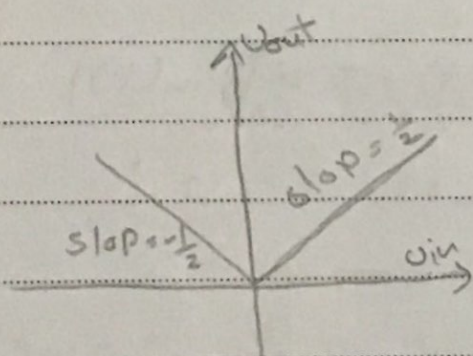
if $V_{in} < 0 \Rightarrow D_1$ off & D_2 on

$$V_o = -V_{in}/2$$

$$V_o = \begin{cases} V_{in}/2 & \text{if } V_{in} \geq 0 \\ -V_{in}/2 & \text{if } V_{in} < 0 \end{cases}$$



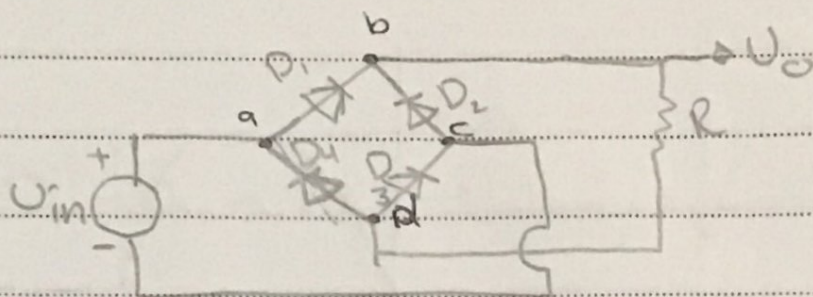
$$\Rightarrow V_o = \frac{1}{2} |V_{in}|$$



$$V_{in} = V_m \sin \omega t$$

$$\Rightarrow V_o = \frac{V_m}{2} |\sin \omega t|$$

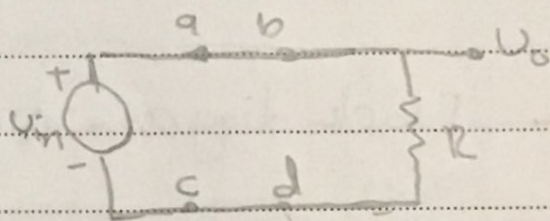
— Bridge Rectifier (FWR) :—



Assume diodes are ideal

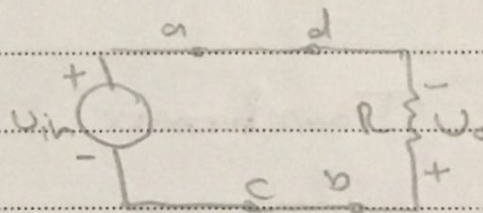
- for $V_{in} > 0 \Rightarrow D_1 \& D_3$ on, $D_2 \& D_4$ off

$$V_o = V_{in}$$



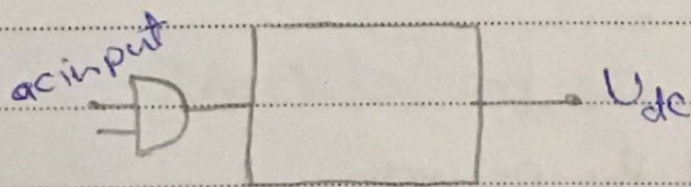
- for $V_{in} < 0 \Rightarrow D_1 \& D_3$ off, $D_2 \& D_4$ on

$$V_o = -V_{in}$$



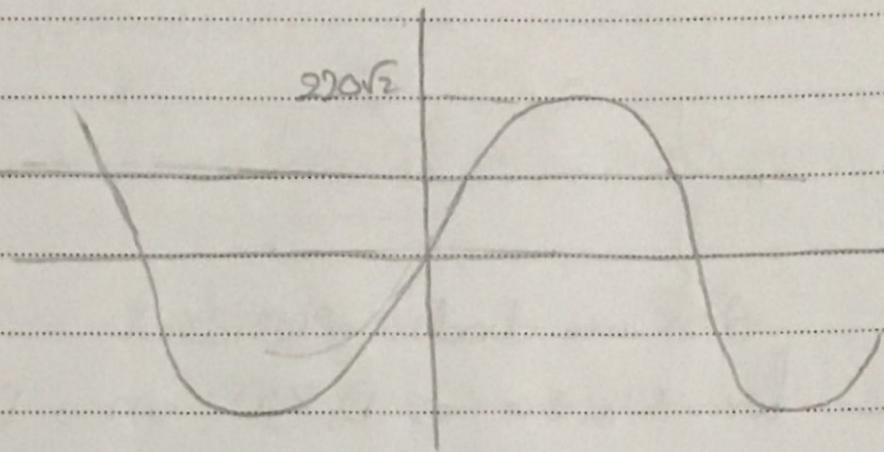
$$\therefore V_o = |V_{in}|$$

* DC power supply:- all Digital crts

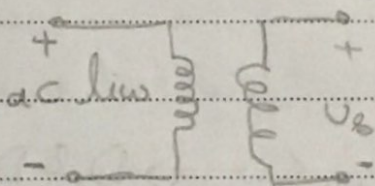


$$220\sqrt{2} \sin \omega t$$

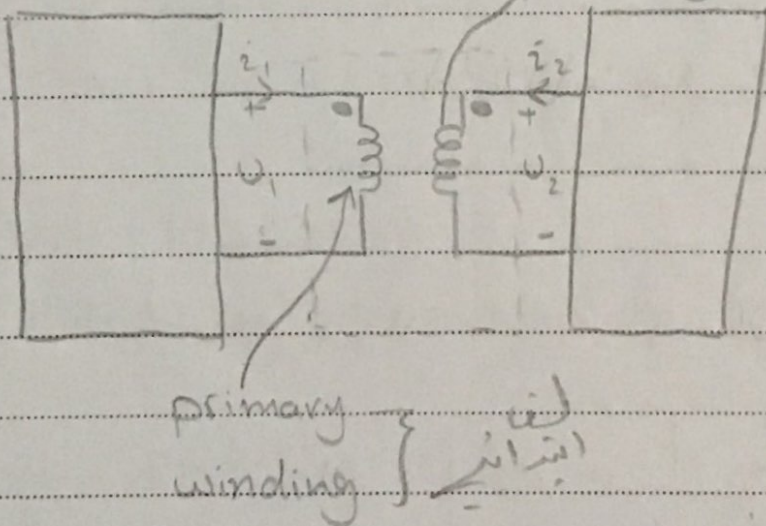
$$\omega = 100\pi \text{ rad/s}$$



- Block diagram of Dc power supply



Transformer (تحوّل) ^{لفائف} secondary winding



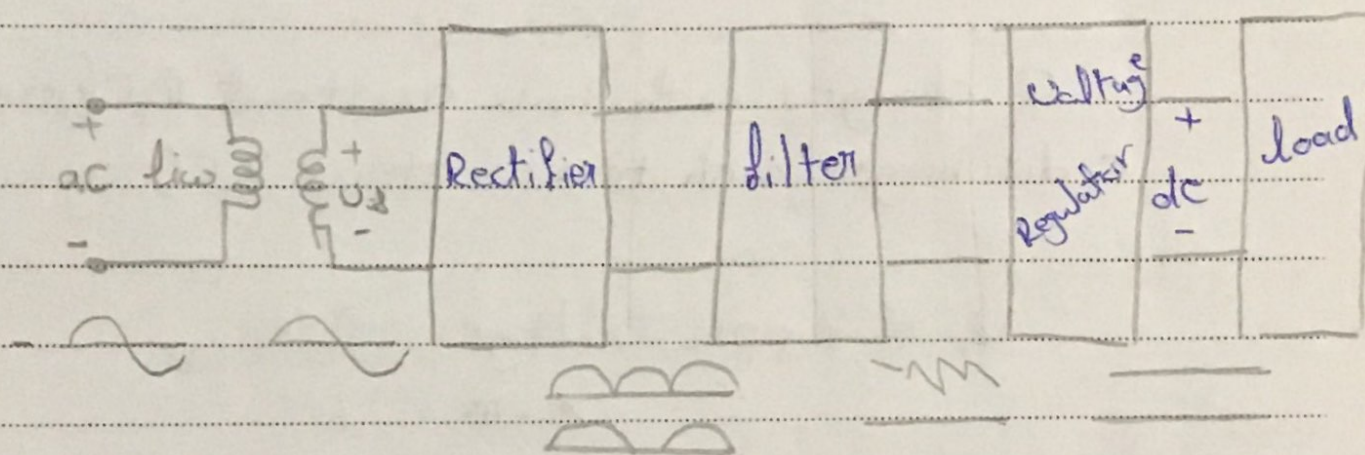
N_1 = # of the primary

N_2 = # of the secondary ^{لفائف}

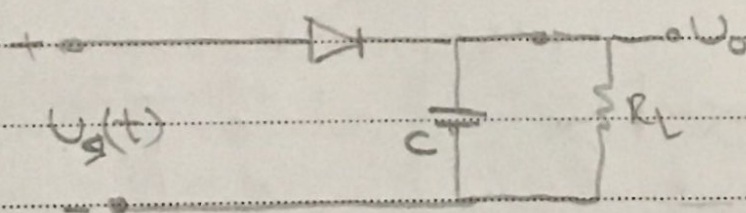
$$P_1 = P_2 \Rightarrow U_1 i_1 = U_2 i_2$$

$$\frac{U_2}{U_1} = \frac{i_1}{i_2}$$

Back to block diagram

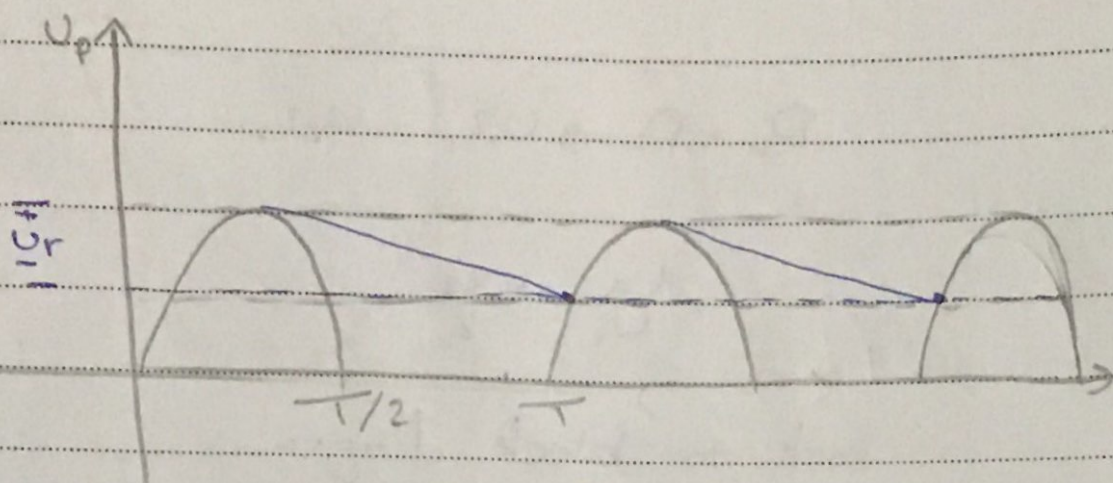


(capacitor) is also (filter)



$$U_s(t) = U_p \sin \omega t, \quad \omega = 2\pi f = \frac{2\pi}{T}$$

$$f = 50 \Rightarrow T = \frac{1}{50} = 20 \text{ ms}$$



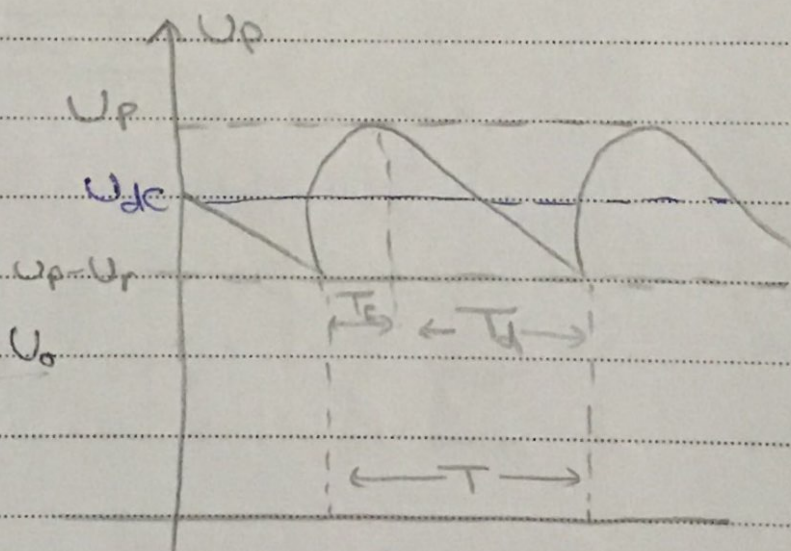
C charges with time constant $R_f C$ (very small)
 C discharges with time constant $R_f C$ (very large)

$U_r \triangleq$ Ripple voltage

دولت‌های U_p
 میانگین U_p
 میانگین U_p
 میانگین U_p
 میانگین U_p

$U_{dc} = \text{average of } U_p$

$$U_{dc} = U_p - \frac{U_r}{2}$$



21512014

Tutorial

Question (eight) :-

$$n_i(T_f) = (N_c N_v)^{3/2} e^{\frac{-E_g}{2k_B T}}$$

$$\frac{n_i(T_1)}{n_i(T_0)} = \left(\frac{T_1}{T_0}\right)^{3/2} e^{\frac{-E_g}{2k_B} \left(\frac{1}{T_1} - \frac{1}{T_0}\right)}$$

constant

$$N_c = n_c T^{3/2}, N_v = n_v T^{3/2}$$

constant

$$I_D = I_S (e^{V_D/V_T} - 1)$$

$$I_D = -I_S = -15 \text{ PA} @ 25^\circ\text{C}$$

$$n_i(75) = n_i(25) \frac{(75+273)}{(25+273)} e^{\frac{-E_g}{2k_B} \left(\frac{1}{318} - \frac{1}{310}\right)}$$

Question (Three) :-

$$V_D = 0 \quad C_j = 19.9 \text{ pF}$$

$$C_j = \frac{C_{j0}}{\sqrt{\phi_0}} \Rightarrow \phi_0 (19.9 \text{ pF})^2 = (C_{j0})^2$$

if junction is step

$$\textcircled{a} \quad V_D = 0.5 \quad C_j = \frac{C_{j0}}{\sqrt{1 + 0.5/\phi_0}} = 17.3$$

$$\sqrt{1 + \frac{0.5}{\phi_0}} = \frac{C_{j0}}{17.3} = \frac{19.9}{17.3}$$

$$\left(1 + \frac{0.5}{\phi_0}\right) = \left(\frac{19.9}{17.3}\right)^2$$

$$\frac{0.5}{\phi_0} = \left(\frac{19.9}{17.3}\right)^2 - 1$$

$$\phi_0 = \frac{0.5}{\left(\frac{19.9}{17.3}\right)^2 - 1}$$

$$G_D = -1$$

$$C_j = \frac{C_j^0}{\sqrt{1 - U_0/\phi_0}}$$

وخطی و استوف اذا لانت التتابع قريبه اذا تقوس
step و اذا خلافت وجهه من هم بعيدا اذا لم يثبت
step و linearly (محاذاة)

PS #4 P. #4

Assume $n_i = 1.5 \times 10^{16} / \text{cm}^3$

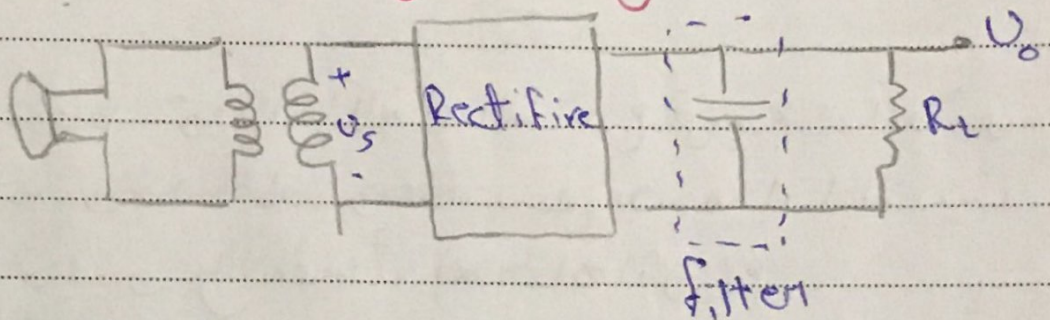
$$\mu_n = 1600 \text{ cm}^2/\text{V.s} \quad \mu_p = 500 \text{ cm}^2/\text{V.s}$$

Life time of minority carriers in p-type

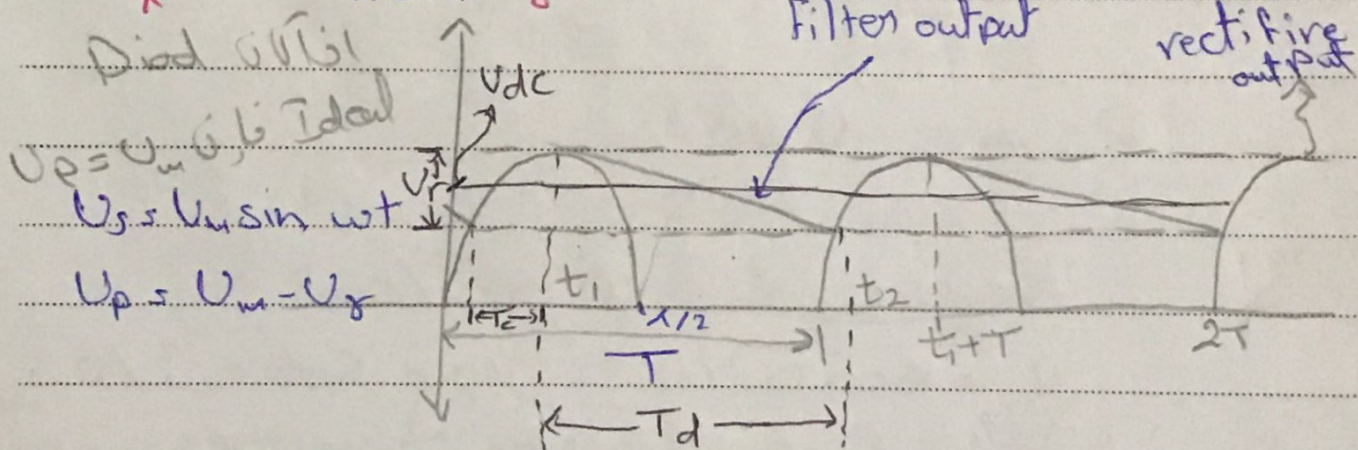
11 12 13 14 15

6/5/2017

* dc power supply (unregulated):-



* for HWR :-



V_r = ripple voltage

V_{dc} = average output voltage = $V_p = V_r/2$

- During T_c , The capacitor charges (Diod is on) with a very small time constant $\tau_c = R_p C$ ($R_p \ll R_L$)

⇒ T_c is very small (compared to T)

- During T_d The capacitor discharges
Diodis off with a very long time
constant $T_d = R_L C$

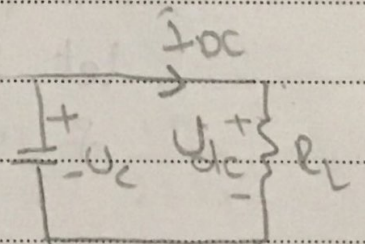
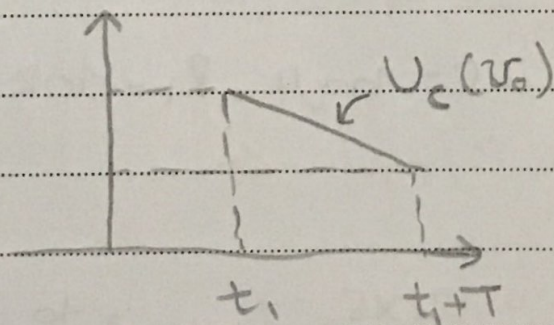
⇒ T_d is very long

- Assumptions:-

$$T_d \cong T, \text{ neglect } T_c$$
$$t_2 \cong t_1 + T$$

- Estimate V_r :-

C discharges @ constant current I_{oc}



let dQ = amount of charge lost by capacitor
during $T_d (T)$

$$\begin{aligned}
 dQ &= Q(t,+) - Q(t,+T) \\
 &= C U_C(t,+) - C U_C(t,+T) \\
 &= C U_P - C [U_P - U_r] \\
 &= C (U_P - (U_P - U_r)) = C U_r
 \end{aligned}$$

$$\text{also } dQ = I_{dc} \bar{I}_d = I_{dc} T = \frac{U_{dc} T}{R_L}$$

$$C U_r = \frac{U_{dc}}{R_L} \Rightarrow U_r = \frac{U_{dc} T}{R_L C} = \frac{U_{dc}}{f R_L C} \left(f = \frac{1}{T} \right)$$

$$U_r = \frac{U_P - U_r/2}{f R_L C} \Rightarrow U_r \left[1 + \frac{1}{2 f R_L C} \right]$$

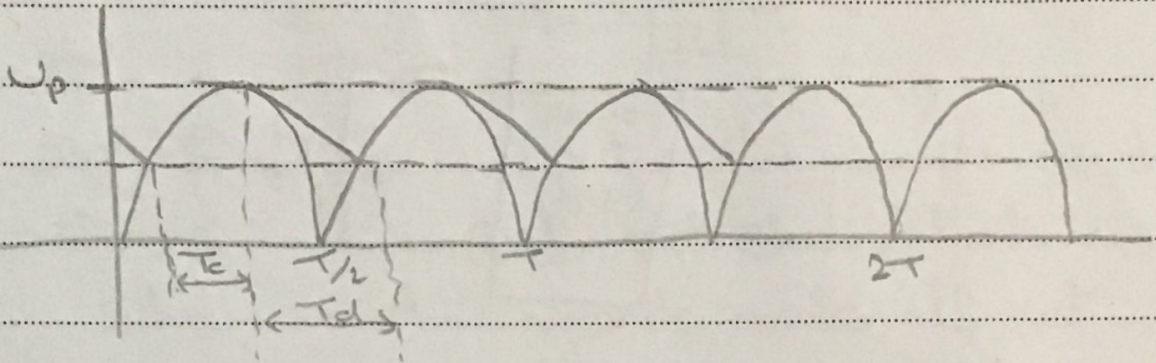
$$= \frac{U_P}{f R_L C} \Rightarrow U_r = \frac{2 U_P}{1 + 2 f R_L C} \approx \frac{U_P}{f R_L C}$$

Example :-

let $U_P = 5V$, $C = 100\mu$, $R_L = 10k\Omega$
 $f = 50$

$$U_r = \frac{2 \times 5}{1 + 2 \times 50 \times 10^{-4} \times 10^4} = \frac{10}{101} \approx 0.1$$

* For (FWR):- $U_{r_{FWR}}$ ال جي جي U_p جي



Neglect $T_c \Rightarrow T_d \cong T/2$

using the same argument

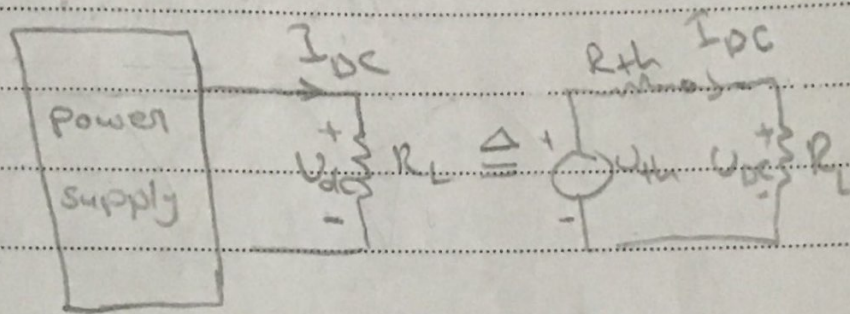
$$U_r = \frac{U_{dc} T_d}{R_L C} = \frac{U_{dc} T}{2R_L C} = \frac{U_{dc}}{2fR_L C}$$

$$\Rightarrow U_r = \frac{U_p - U_r/2}{2fR_L C}$$

$$\Rightarrow U_r \left[1 + \frac{1}{4fR_L C} \right] = \frac{U_p}{2fR_L C}$$

$$U_r = \frac{2U_p}{1 + 4fR_L C} \cong U_p / 2fR_L C$$

Thvenin's equivalent circuit of dc power supply :-

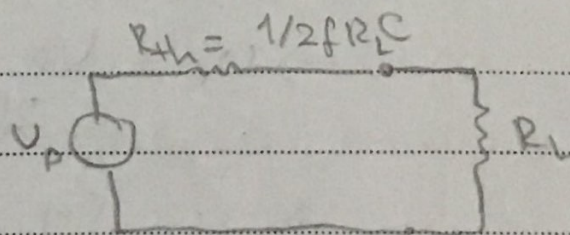


$$V_{dc} = V_p - V_r/2$$

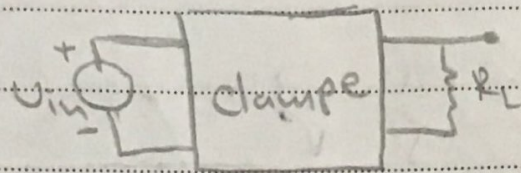
for AWR :-

$$V_{dc} = V_p - \frac{V_p}{2fR_LC}$$

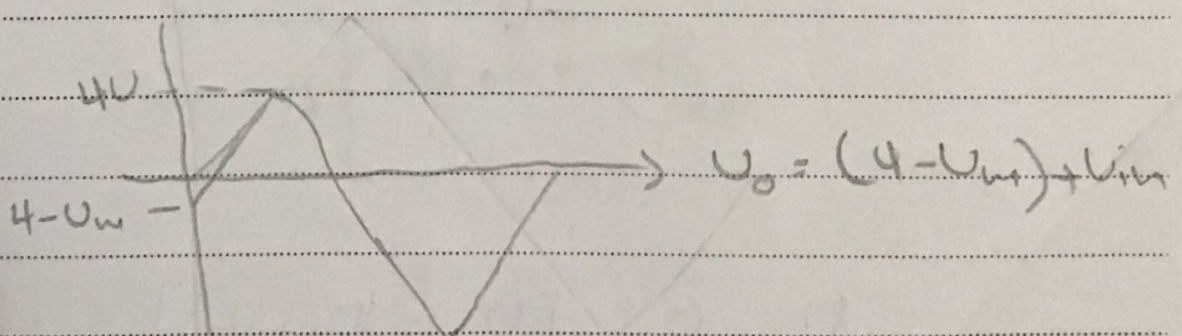
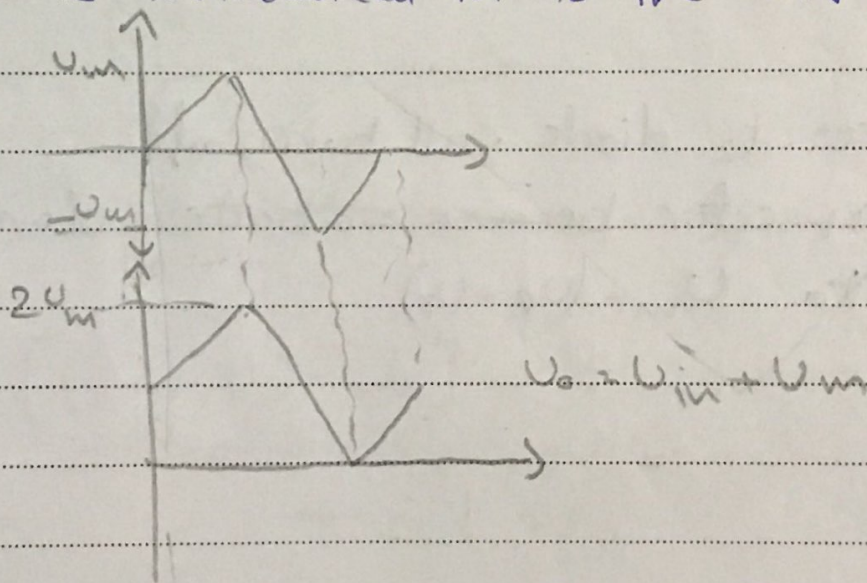
$$V_p = V_{dc} + I_{dc} R_{th}$$

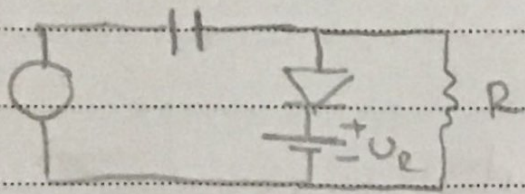


* Clamping circuits:-

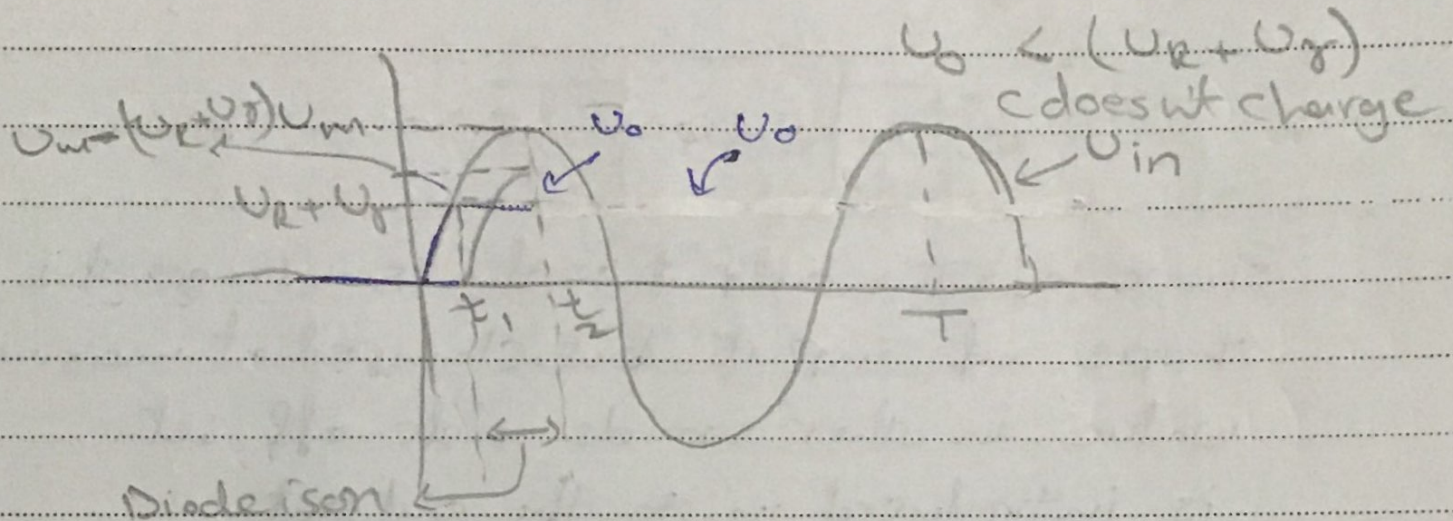


shape of the output is the same as the shape of input but clamped at maximum value in other words a dc off set is introduced in to the output



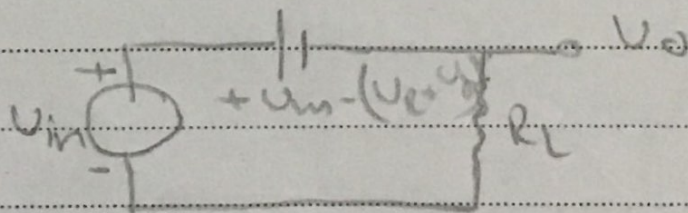


R is very large
Diode is off if $T \ll RC$



After t_2 diode will turn off
 \Rightarrow capacitor becomes as battery charged to $U_m - (U_R + U_D)$

$$U_o = U_m - \delta - [U_m - (U_R + U_D)] \\ = (U_R + U_D) - \delta \rightarrow \text{detta}$$



$$U_o = U_m - [U_m - (U_R + U_D)]$$

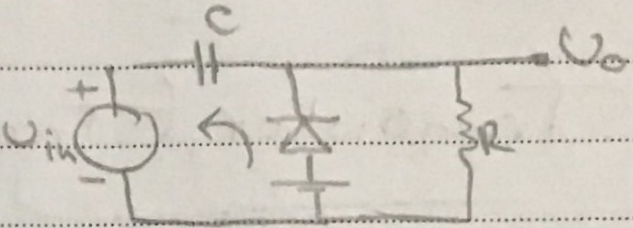
Condition for clamping
 $T \ll RC$

$$U_{in} > (U_R + U_D)$$

Subject:

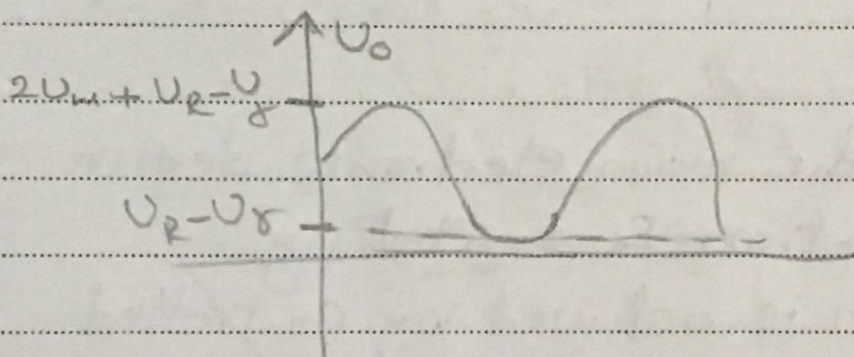
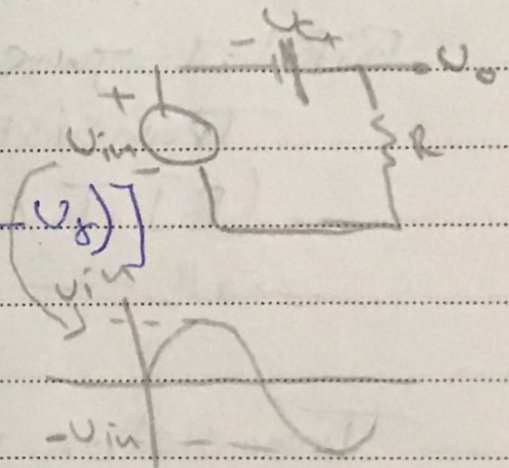
— another clamper :-

Capacitor charges to $(V_R - V_S) - (-V_m)$



$$V_C = V_m + (V_R - V_S)$$

$$V_o = v_{in} + [V_m + (V_R - V_S)]$$



Condition for clamping

$$T \ll RC$$

$$(V_R - V_S) > -V_m$$

9/5/2017

Transistor (Transistor resistor):-

Bi Polar junction

Transistor

(BJT)

الترانزستور

Field Effect

Transistors

(FETs)

الترانزستور

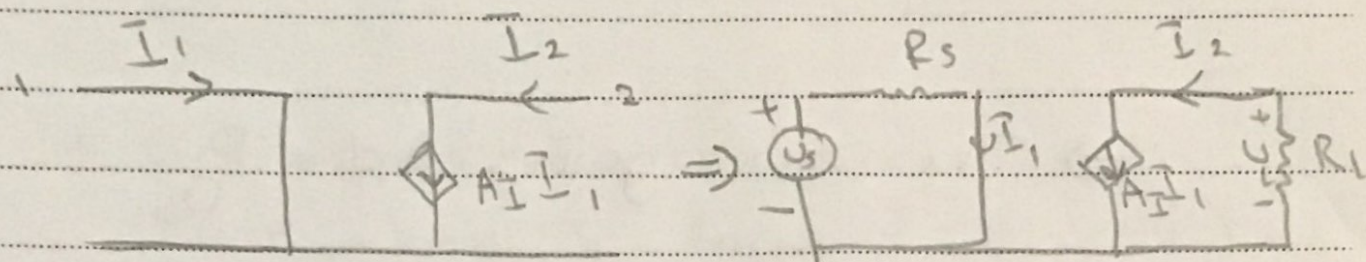
Transistor is the main electronic device for amplification & switching

- Amplification is achieved by controlled source

- Transistor exhibit controlled source characteristics

Controlled sources:-

- Ideal current controlled source:-



I deal CCCS

$$U_L = -R_L I_2 = -R_L A_I I_1$$

$$I_1 = \frac{U_S}{R_S}$$

$$U_L = -A_I \frac{R_L}{R_S} U_S$$

\Rightarrow The ^{current} gain = $\frac{I_2}{I_1} = A_I$

The voltage gain $\triangleq A_U = \frac{U_L}{U_S} = -A_I \frac{R_L}{R_S}$

if $U_S = 20 \sin \omega t$ (mV), $A_I = 100$, $R_L = 4 \Omega$, $R_S = 1$

$$\Rightarrow A_U = -100 \times \frac{4}{1} = -400$$

$$U_L = A_U U_S = -8000 \sin \omega t \text{ mV}$$

$$= -8 \sin \omega t \text{ V}$$

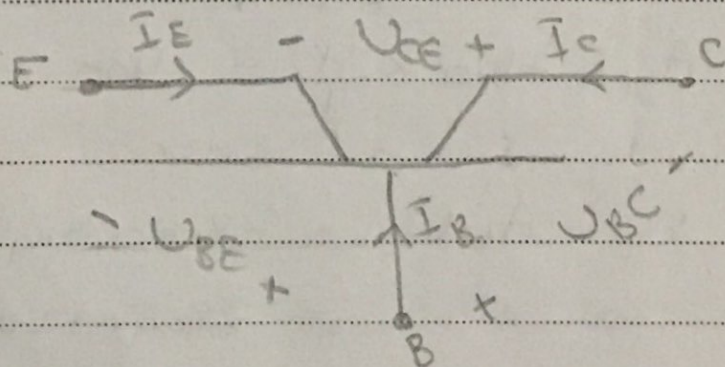
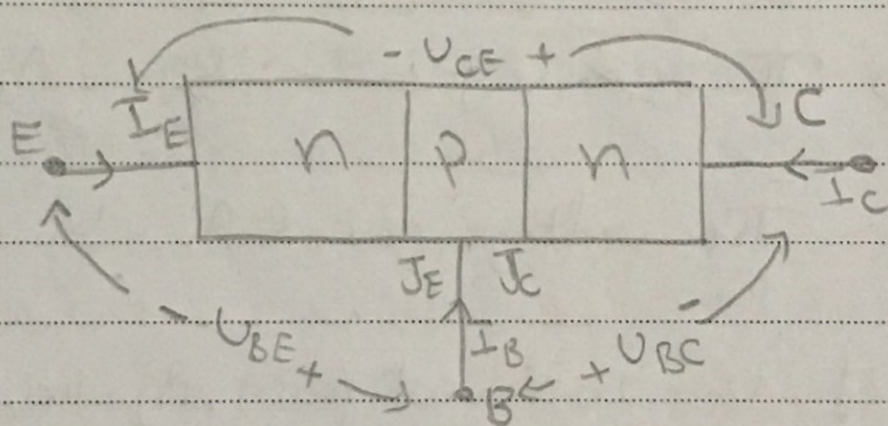
\Rightarrow The Power gain: $A_p = \frac{P_L}{P_S}$

$$P_L = I_2^2 R_L, \quad P_S = R_S I_1^2$$

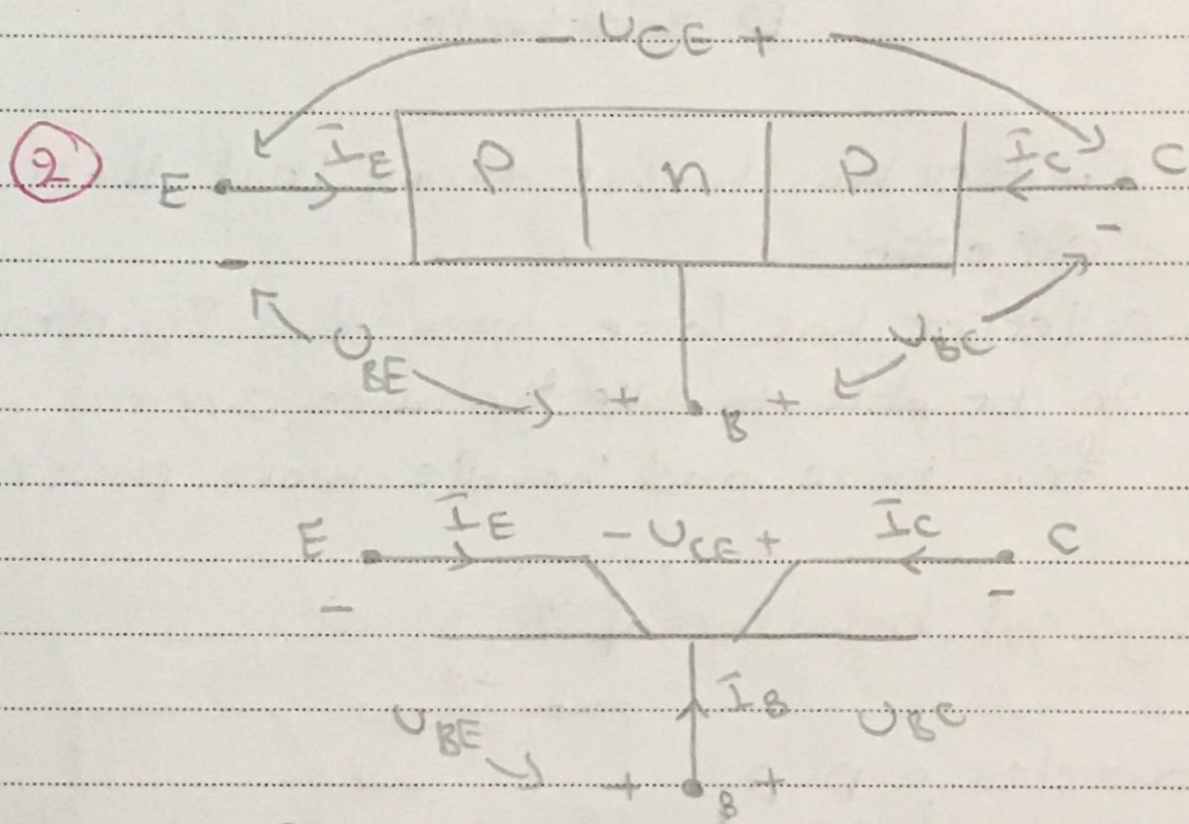
$$A_p = \frac{R_L}{R_S} \frac{I_2^2}{I_1^2} = \frac{R_L}{R_S} \left(\frac{I_1 A_I}{I_1} \right)^2 = A_I^2 \frac{R_L}{R_S}$$

BJTs (Two types):

①

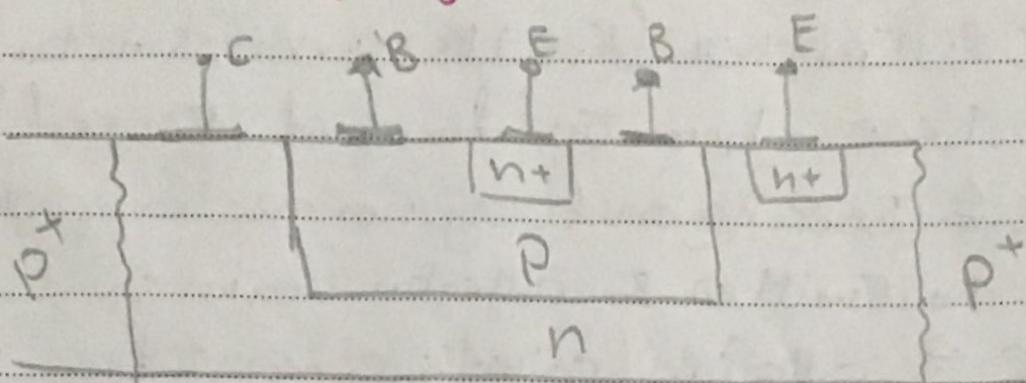


- ② $E \triangleq$ Emitter (Emitts carriers into Base when J_E forward Biased).
- $B \triangleq$ Base Region (Very narrow compared to Emitter & collector regions)
- $C \triangleq$ collector (collects carriers from Base).



PNP second Type.

structure of BJT

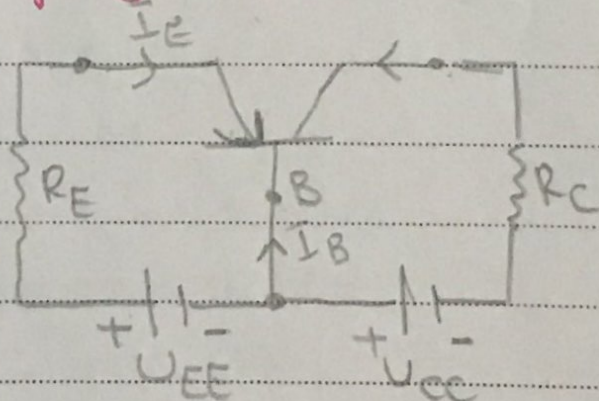


P substrate

- Emitter has higher doping level than collector
- collector has large area than Emitter to be able to collect more carriers from base and handle more power

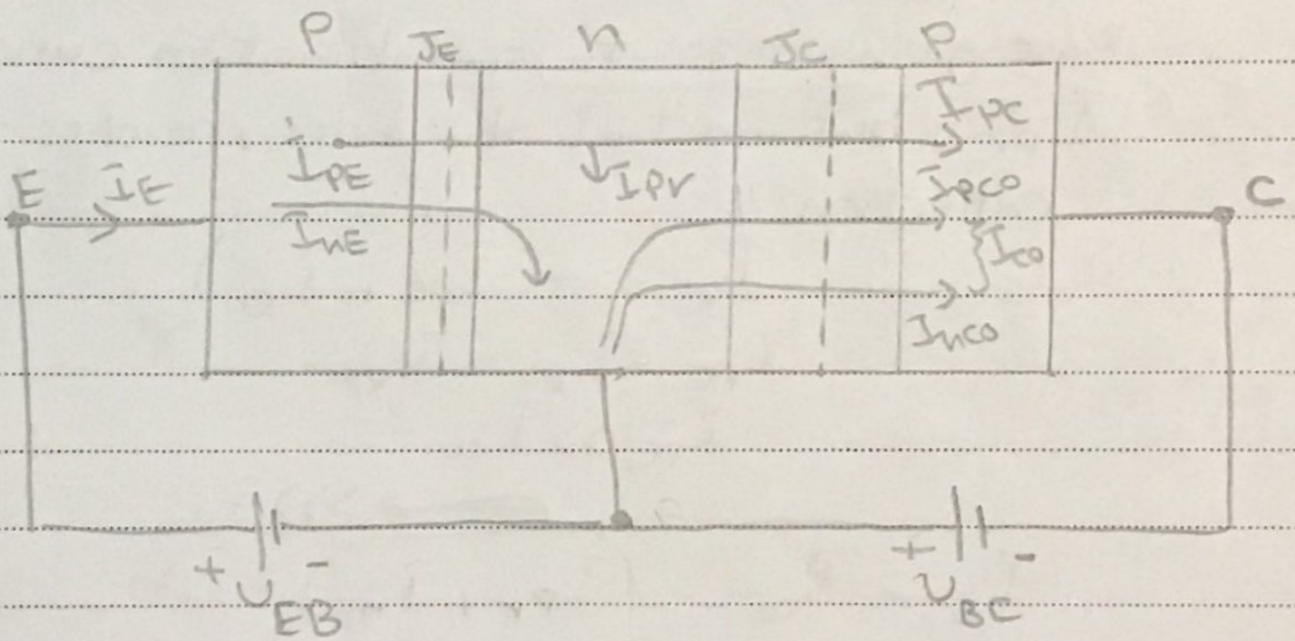
physical behavior of BJT :-

consider a pnp with TE forward Biased & I_c reverse biased



Remember:-

- V_{EB} (V_{CB}) appear directly across the junction J_E & J_C respectively
- no drift current in neutral region
- \Rightarrow All current component in a BJT are diffusion currents.



- if E is open \Rightarrow reverse saturation current

I_{CO} flow cross J_C

$$I_{CO} = I_{PCO} + I_{NCO}$$

due to electron from collector to Base

I_{PCO} \leftarrow holes

$$\bar{I}_E = \bar{I}_{PE} + \bar{I}_{nE} \rightarrow \text{Electron injected into E from B}$$

$$\bar{I}_E, \text{ holes emitted into B from E}$$

- $\bar{I}_{nE} \ll \bar{I}_{PE}$ (because base is lightly doped compared to Emmitter)

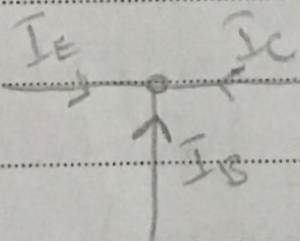
- some of holes injected into base from Emmitter recombine with electrons in the Base giving rise to recombination current \bar{I}_{pr} , but most of the holes, reaches the collector

$$\bar{I}_C = -(\bar{I}_{PC} + \bar{I}_{CO})$$

$$\bar{I}_{PC} = \bar{I}_{PE} - \bar{I}_{pr}$$

$$\bar{I}_{PC} \gg \bar{I}_{CO}$$

$$\bar{I}_B = \bar{I}_{CO} - (\bar{I}_{pr} + \bar{I}_{nE})$$



$$\bar{I}_E + \bar{I}_C + \bar{I}_B = 0$$

$$V_{EB} + V_{BC} + V_{CE} = 0 \text{ around the loop}$$

$$\bar{I}_E \approx \bar{I}_{CO} \approx \bar{I}_{pr} \approx \bar{I}_{nE}$$

Common Base current gain (α) :-

$$\alpha = \frac{I_{PC}}{I_E} = -\frac{I_C - I_0}{I_E}$$

for high gain (α) should be close to unity -

$$\alpha = \gamma \alpha_T M \rightarrow \text{collector multiplication factor}$$

\downarrow Base Transport factor

\downarrow Emitter efficiency

$$\gamma = \frac{I_{PE}}{I_E} = \frac{I_{PE}}{I_{PE} + I_{NE}} = \frac{1}{1 + \frac{I_{NE}}{I_{PE}}}$$

$$\alpha_T = \frac{I_{PC}}{I_{PE}}, \quad M = -\frac{(I_C - I_{C0})}{I_{PC}}$$

$$\Rightarrow \alpha = \gamma \alpha_T M = -\frac{(I_C - I_{C0})}{I_E}$$

Condition for α to be close to unity:-

① Need α close to unity

$$\Rightarrow \frac{I_{nE}}{I_{pE}} \text{ (very small)} \rightarrow \alpha$$

\Rightarrow E is heavily doped compared to B

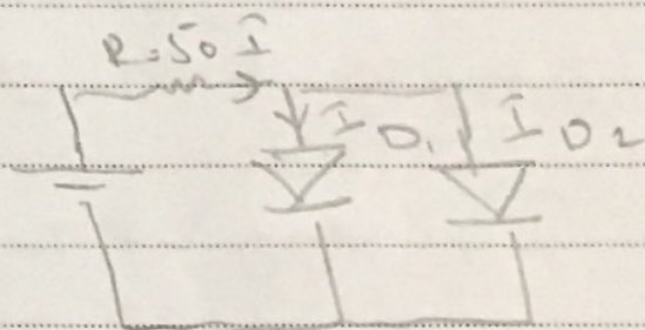
② α_r close to unity

\Rightarrow reduce $I_{pr} \Rightarrow$ reduce base width

\Rightarrow make collector area large

Tutorial

Q6)



$$V_{D1} = V_{D2}$$

$$I_{S1} = I_{S2} = I_S (e^{V_D/V_T} - 1)$$

$$I = 2I_D = \frac{V - V_D}{R} \rightarrow (2)$$

$$I_{D1} = I_{D2} = I_S (e^{V_D/V_T} - 1) = I_D \quad (1)$$

$$(1) - (2)$$

Q5

forward $\Rightarrow e^{V_D/V_T} \gg 1$

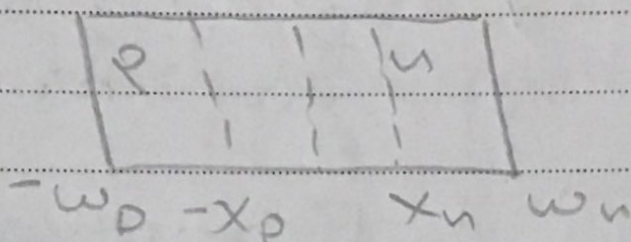
$$I_D = I_S e^{V_D/V_T}$$

assume V_T

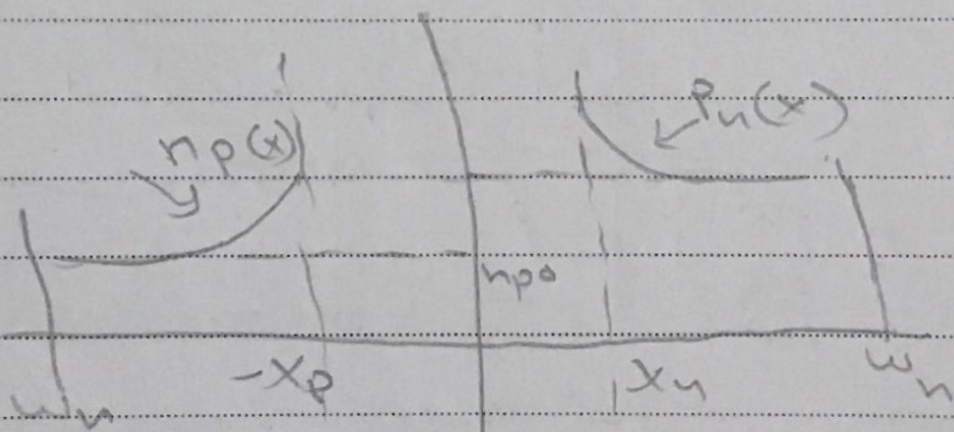
Sum of the problem:-

minority carrier profile of forward biased p-n junction

3) long base Diode



$$(w_n - x_n) \gg L_p, w_p - x_p \gg L_n$$



$$\begin{aligned} p_n(x) &= p_{n0} + p'_n(x) \\ &= p_{n0} + p'_n(x_n) e^{-(x-x_n)/L_p} \\ p'_n(x_n) &= p_n(x_n) - p_{n0} \end{aligned}$$

$$\Rightarrow P_n(x) = P_n(x_n) e^{-(x-x_n)/L_p}$$

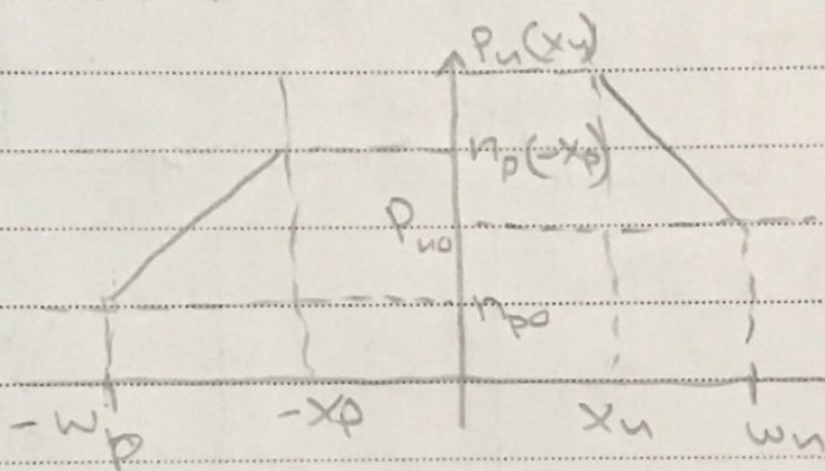
$$P_n(x_n) = P_{n0} e^{V_0/V_T}$$

$$n_p(x) = n_{p0} + n'_p(x_p) e^{(x+x_p)/L_n}$$

$$\hookrightarrow n_p(-x_p) = n_{p0} e^{V_0/V_T}$$

$$n'_p(x) = n'_p(-x_p) e^{(x+x_p)/L_n}$$

II) short base diode



$$(w_n - x_n) \ll L_p, (w_p - x_p) \ll L_n$$

$$P_n(x_n) = P_{n0} e^{V_0/V_T}$$

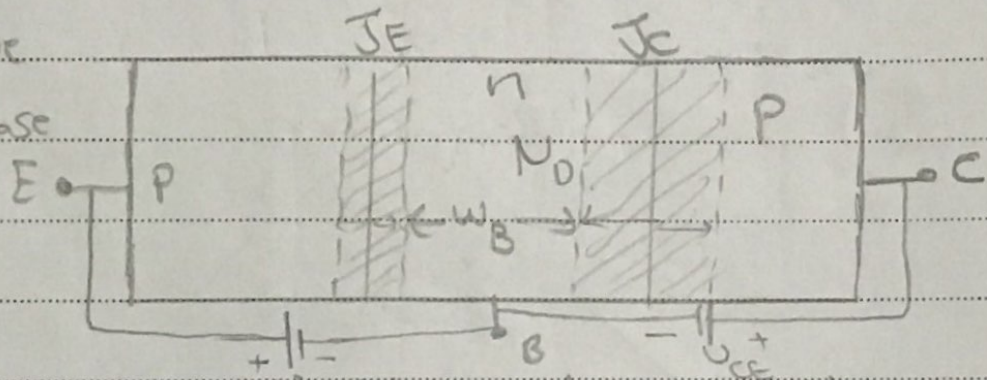
$$n_p(-x_p) = n_{p0} e^{V_0/V_T}$$

13/5/2017

why Base is narrow??

Consider a pnp with wide base region with J_E forward Biased & J_C junction reverse biased

w_B = effective width of Base region

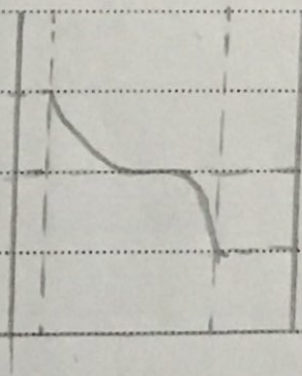


$$P_{n0} = \frac{n_i^2}{N_0}$$

$$P_{n0} e^{V_{EB}/U_T}$$

$$V_{EB} > 0$$

$$P_{n0}$$



$$V_{CB} < 0$$

$$w_B \gg L_p$$

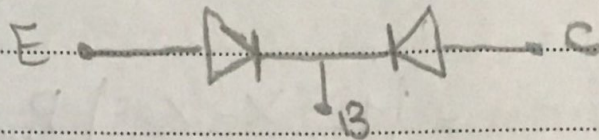
$$P_{n0} e^{V_{CB}/U_T}$$

Practically all holes injected into the Base region at J_E junction are lost by recombination with electrons

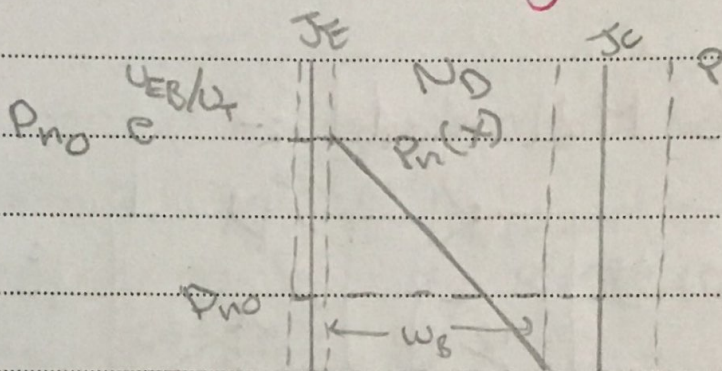
\Rightarrow None reaches J_C junction

\Rightarrow No transistor action

⇒ Effectively The two junctions represent Two independent non-interacting back to back diodes



— For narrow Base region ($w_B \ll l_p$) :-



⇒ most holes injected into Base from emitter reach the collector

$P_n(x)$ decays exponentially in the Base region.

$$P_n(x) = \underbrace{P_{n0} e^{V_{EB}/V_T}}_{P_n(x_{nE})} e^{-(x-x_{nE})/l_p}$$

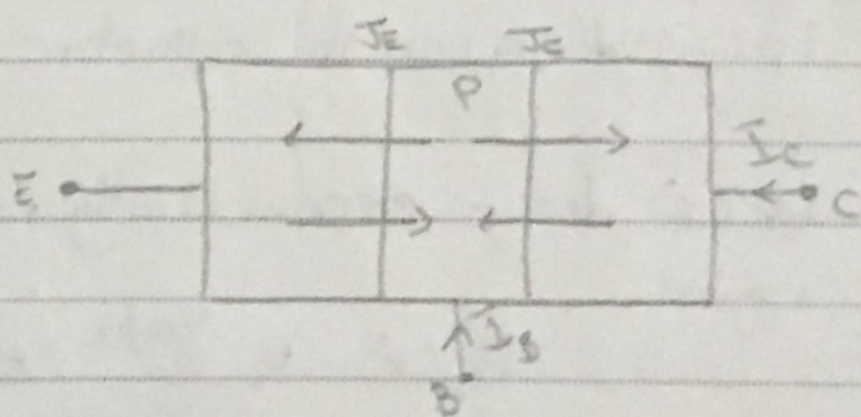
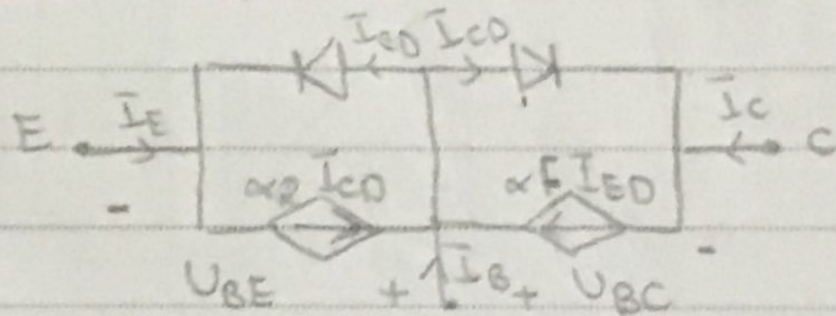
(J_E f.b, J_C R.b)

$P_n(x)$ decays linearly in the Base region

$$P_n(x) = P_{n0} e^{V_{BE}/V_T} - P_{n0} e^{V_{BE}/V_T}$$

$$= \left(1 - \frac{x - x_{BE}}{w_B}\right) P_{n0} e^{V_{BE}/V_T}$$

Ebber's Mall model :-



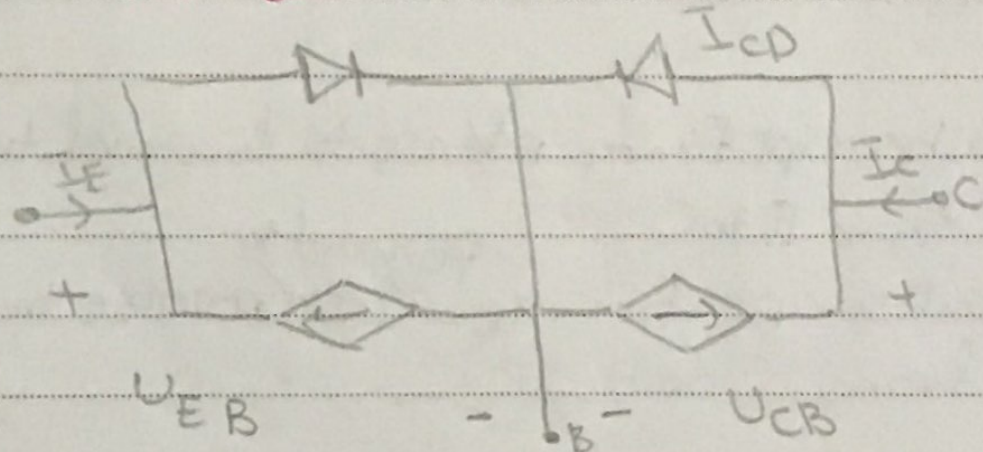
$\alpha_F I_{EO} =$ fraction of I_{EO} coupled into collector
 $\alpha_R I_{EO} =$ " " I_{EO} " " Emitter

L_B = Diffusion length of minority carriers in Base region

N_B = Doping level in Base region

w_B = Effective width of Base region

Pnp \Rightarrow



$$I_E = I_{ED} - \alpha_R I_{CD} = I_{ES} (e^{-U_{EB}/U_T} - 1) - \alpha_R I_{CS} (e^{-U_{CB}/U_T} - 1)$$

$$I_C = I_{CD} - \alpha_F I_{ED} = I_{CS} (e^{-U_{CB}/U_T} - 1) - \alpha_F I_{ES} (e^{-U_{EB}/U_T} - 1)$$

Typical values for α_F & α_R :-

$$0.98 \leq \alpha_F \leq 0.998$$

$$0.4 \leq \alpha_R \leq 0.8$$

Large signal current gain :-

consider the npn with J_E forward Biased and J_C reverse biased by short circuiting

$$(V_{BE} = V_{CE}, V_{BC} = 0)$$

$$I_{CB} = I_{ES} (e^{V_{BC}/V_T} - 1) = 0$$

$$I_E = -I_{ED} = -I_{ES} (e^{V_{BE}/V_T} - 1)$$

$$I_C = \alpha_F I_{ED} = \alpha_F I_{ES} (e^{V_{BE}/V_T} - 1) = -\alpha_F I_E$$

$$\alpha_F = \left. \frac{-I_C}{I_E} \right|_{V_{BC}=0}$$

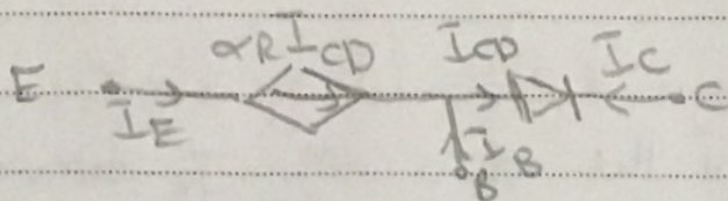
for both pnp & npn

$\alpha_F \triangleq$ common base forward short circuit current gain

For pnp & npn

If J_C Forward Biased & $V_{BE} = 0$ ($V_{BE} = V_{CE}$)

$$\Rightarrow I_{CB} = 0, I_{CB} = I_{ES} (e^{V_{BC}/V_T} - 1)$$



$$I_C = -I_{CD} = -I_{CS} (e^{V_D/V_T} - 1)$$

$$I_E = \alpha_R I_{CD} = -\alpha_R I_C$$

for both
PNP & NPN

$$\alpha_R = \frac{-I_E}{I_C} \Big|_{V_{CE}=0} \triangleq \text{common base reverse shortcircuit current gain}$$

$$I_B = -(I_C + I_E)$$

for T_E f.b. & $V_{BC}=0$

$$I_B = -(-\alpha_F I_E + I_E) = -(1 - \alpha_F) I_E$$

Express I_C & I_E in terms of I_B

$$I_E = \frac{-\alpha_F}{1 - \alpha_F} I_B \triangleq \beta_F I_B$$

$$\beta_F = \frac{\alpha_F}{1 - \alpha_F}$$

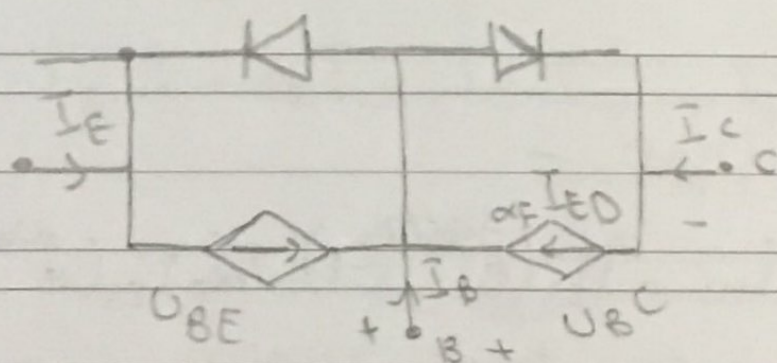
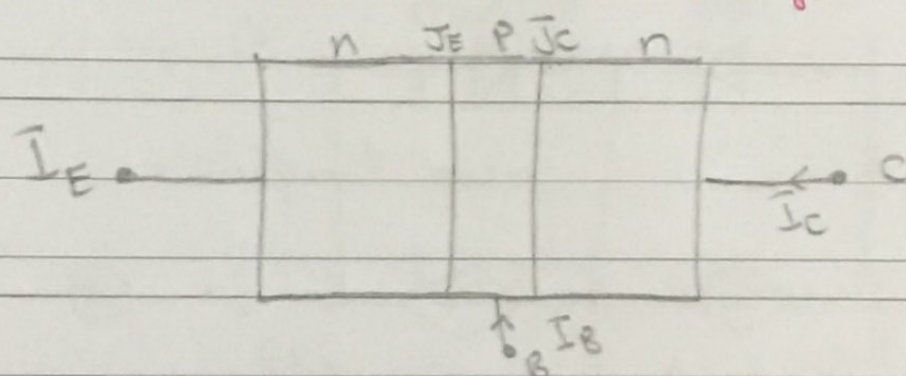
$$1 + \beta_F = \frac{1 - \alpha_F}{1 - \alpha_F} + \frac{\alpha_F}{1 - \alpha_F}$$

$$= \frac{1}{1 - \alpha_F}$$

$$\Rightarrow I_E = -(1 + \beta_F) I_B$$

β_F = Common Emitter forward short circuit current gain

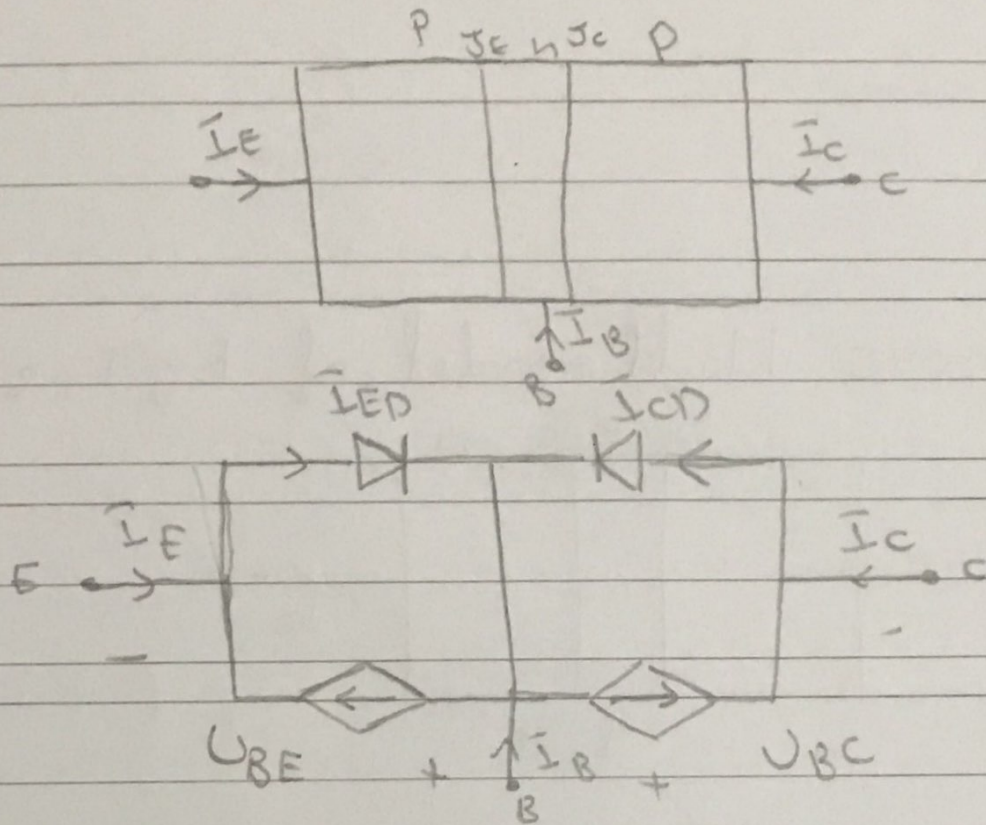
Ebers Moll model of BJT :-



$$I_C = \alpha_F I_{ED} - I_{CD} = \alpha_F I_{ES} (e^{U_{BE}/U_T} - 1) - I_{CS} (e^{U_{BC}/U_T} - 1)$$

$$I_E = \alpha_R I_{CD} - I_{ED} = \alpha_R I_{CS} (e^{U_{BC}/U_T} - 1) - I_{ES} (e^{U_{BE}/U_T} - 1)$$

for (npn)



for pnp:-

$$I_C = I_{ED} - \alpha_F I_{ED} = I_{CS} (e^{-U_{BC}/U_T} - 1) - \alpha_F I_{ES} (e^{-U_{BE}/U_T} - 1)$$

$$I_E = I_{ED} - \alpha_R I_{CD} = I_{ES} (e^{-U_{BE}/U_T} - 1) - \alpha_R I_{CS} (e^{-U_{BC}/U_T} - 1)$$

large signal current gains:-

consider npn:-

* if J_E f.b & J_C reverse biased by

$$U_{BC} = 0.$$

$$\bar{I}_E = -\bar{I}_{ED} = -\bar{I}_{ES} (e^{U_{BE}/U_T} - 1)$$

$$\bar{I}_C = \alpha_F \bar{I}_{ED} = -\alpha_F \bar{I}_E \Rightarrow \alpha_F = \frac{\bar{I}_C}{\bar{I}_E}$$

$\alpha_F \triangleq$ common base forward short-circuit current gain

⊛ if J_C f.b & J_E reverse biased by $U_{BE} = 0$

$$\bar{I}_E = -\alpha_R \bar{I}_C, \bar{I}_C = \bar{I}_C \Rightarrow \bar{I}_E = -\alpha_R \bar{I}_C$$

$$\Rightarrow \alpha_R = \left. \frac{-\bar{I}_E}{\bar{I}_C} \right|_{U_{BE}=0}, \alpha_R \triangleq \text{common base}$$

reverse short circuit current gain

Note :-

$$\bar{I}_C, \bar{I}_E \text{ to } \bar{I}_B$$

$$\bar{I}_B = -(\bar{I}_C + \bar{I}_E)$$

* if J_E is forward.b & $U_{BC} = 0$

$$\bar{I}_B = -(\bar{I}_C + \bar{I}_E) = -(1 - \alpha_F) \bar{I}_E$$

$$\Rightarrow \bar{I}_E = \frac{1}{1-\alpha_F} \bar{I}_B$$

$$\bar{I}_C = \frac{\alpha_F}{1-\alpha_F} \bar{I}_B = \beta_F \bar{I}_B$$

$$\beta_F \triangleq \frac{\bar{I}_C}{\bar{I}_B} \bigg|_{U_{BE}=0} \triangleq \text{common Emitter forward short circuit current gain}$$

* if \bar{I}_C f.b & $U_{BE} = 0$

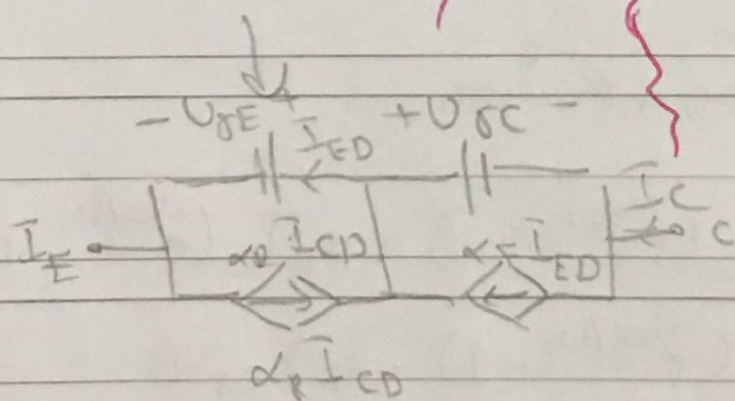
$$\bar{I}_B = -(\bar{I}_E + \bar{I}_C) = -(1-\alpha_R)\bar{I}_C \Rightarrow \bar{I}_C = -\frac{1}{1-\alpha_R} \bar{I}_B$$

$$\bar{I}_E = \frac{\alpha_R}{1-\alpha_R} \bar{I}_B = \bar{I}_E = \beta_R \bar{I}_B$$

$$\beta_R = \frac{\bar{I}_E}{\bar{I}_B} \bigg|_{U_{BE}=0} = \text{Common Emitter Reverse short circuit current}$$

Region of operation of BJT :-

Region	J_E	J_C	action
cut-off	R.B	R.B	I_E & I_C in order of Reverse saturation (current ≈ 0) acts as open circuit
Forward active	F.B	F.B	BJT acts as cccs (Amplifire)
Inverse active	R.B	F.B	
saturation	F.B	F.B	$V_{CE} = V_{CE\text{sat}} = V_{BE} - V_{BC} \approx 0.2V$ BJT acts as (closed switch



$$V_{CE} = V_{BE} - V_{BC}$$

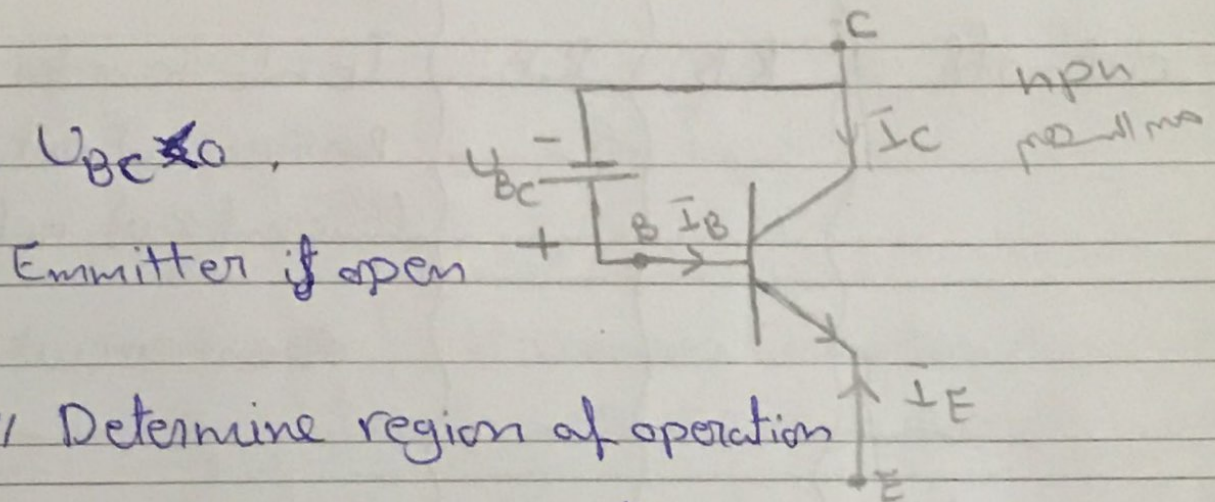
$$\text{saturation} = V_{CE\text{sat}}$$

Subject: _____

* النظم خارج القاعدة (npn)

* النظم داخل القاعدة (pnp)

Example: -



a// Determine region of operation

b// Determine Base & collector currents

BJT is npn

a// $I_E = 0$, $V_{BE} < 0 \Rightarrow J_c$ is R.b

\Rightarrow Region of operation is either cut-off or forward active.

$$I_E = 0 = -I_{ES} + \alpha_R I_{CS}$$

$$= -I_{ES} (e^{V_{BE}/V_T} - 1) + \alpha_R I_{CS} (e^{V_{BC}/V_T} - 1)$$

$$= -I_{ES} (e^{V_{BE}/V_T} - 1) - \alpha_R I_{ES} \approx 0$$

$$\frac{e^{V_{BE}/V_T}}{e} = 1 - \frac{\alpha_R I_{CS}}{I_{ES}} = 1 - \alpha_R$$

$$\Rightarrow (1 - \alpha_F) < 1$$

$$e^{V_{BE}/U_T} < 1 \Rightarrow V_{BE} < 0$$

$$\Rightarrow J_E \text{ is R.B}$$

\Rightarrow Region of operation is cut-off

$$b// I_C = \alpha_F I_{ES} (e^{V_{BE}/U_T} - 1) - I_{CS} (e^{V_{BC}/U_T} - 1)$$

$$= +\alpha_F I_{ES} (e^{V_{BE}/U_T} - 1) + I_{CS}$$

$$= +\alpha_F I_{ES} \left(-\frac{\alpha_R I_{CS}}{I_{ES}} \right) + I_{CS}$$

$$= (1 - \alpha_R \alpha_F) I_{CS} = I_{CO} \quad \text{(Reverse collector current)}$$

(open) given emitter-base voltage

$$I_B = -I_C = -I_{CO}$$

$$c// \text{ let } I_{ES} = 1 \mu A, I_{CS} = 2 \mu A, \alpha_F = 99$$

$$\text{find } V_{BE}, I_C$$

$$\begin{aligned} \frac{V_{BE}}{V_T} &= 1 - \alpha_F = 0.01 \Rightarrow V_{BE} = V_T \ln 0.1 \\ &= -0.115 \text{ V} \end{aligned}$$

$$\begin{aligned} \alpha_R \bar{I}_{CS} &= \alpha_F \bar{I}_{ES} \Rightarrow \alpha_R = \frac{\alpha_F \bar{I}_{ES}}{\bar{I}_{CS}} = \frac{0.99 \times 1 \text{ fA}}{2 \text{ fA}} \\ &= 0.495 \end{aligned}$$

$$\therefore \bar{I}_C = \bar{I}_B = (1 - \alpha_R \alpha_F) \bar{I}_{CS} = 1.02 \text{ fA}$$

* The common base (CB) characteristics:-

- input characteristics :- \bar{I}_E in terms of V_{BE}, V_{BC}

- output characteristics :- \bar{I}_C in terms of \bar{I}_E, V_{BE}

consider an npn :-

⊛ output characteristic

$$\textcircled{1} \quad \bar{I}_E = -\bar{I}_{ES} (e^{V_{BE}/V_T} - 1) + \alpha_R \bar{I}_{CS} (e^{V_{BC}/V_T} - 1)$$

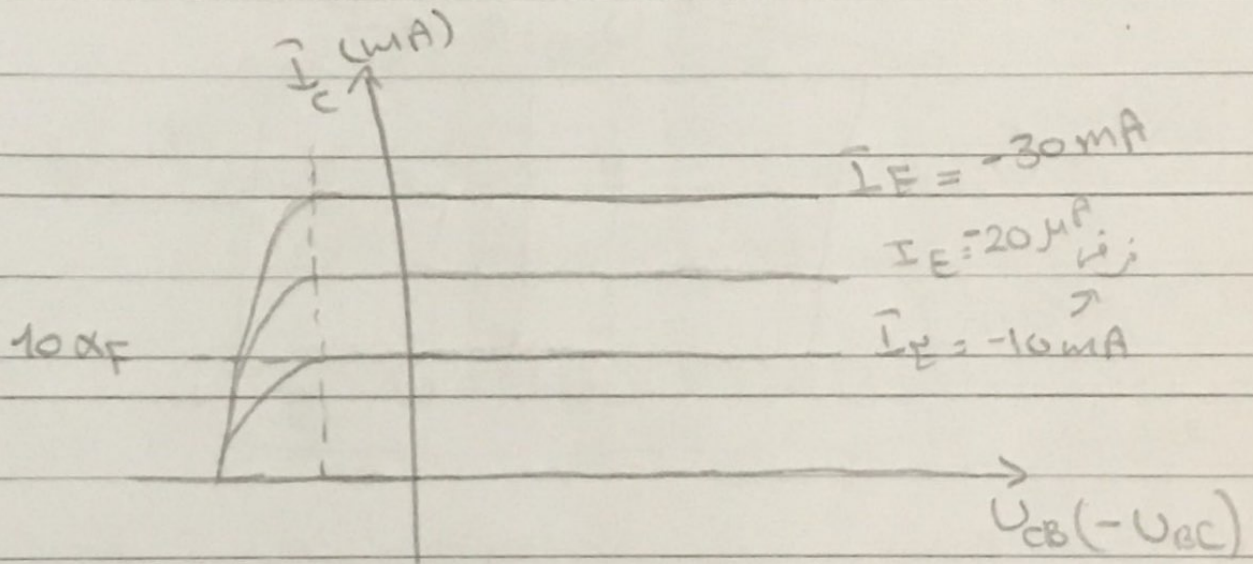
$$\textcircled{2} \quad \bar{I}_C = -\bar{I}_{ES} (e^{V_{BC}/V_T} - 1) + \alpha_F \bar{I}_{ES} (e^{V_{BE}/V_T} - 1)$$

$$\text{from } \textcircled{1} \quad \bar{I}_{ES} (e^{V_{BE}/V_T} - 1) = \bar{I}_E + \alpha_R \bar{I}_{CS} (e^{V_{BC}/V_T} - 1)$$

$$= -(1 - \alpha_R \alpha_F) \bar{I}_{CS} (e^{V_{BC}/V_T} - 1) + \alpha_F \bar{I}_E$$

output characteristic

$$\bar{I}_C = \bar{I}_{CO} (e^{V_{BC}/V_T} - 1) - \alpha_F \bar{I}_E$$



— The forward active region

$$\bar{I}_C \approx -\alpha_F \bar{I}_E \Rightarrow \bar{I}_C \text{ independent of } V_{BC} \\ \text{depends only } \bar{I}_E$$

$$\underset{\alpha=1}{\approx} -\bar{I}_E$$

$$\bar{I}_E = 0 \rightarrow \bar{I}_C = -\bar{I}_{CO} \text{ (cut-off)}$$

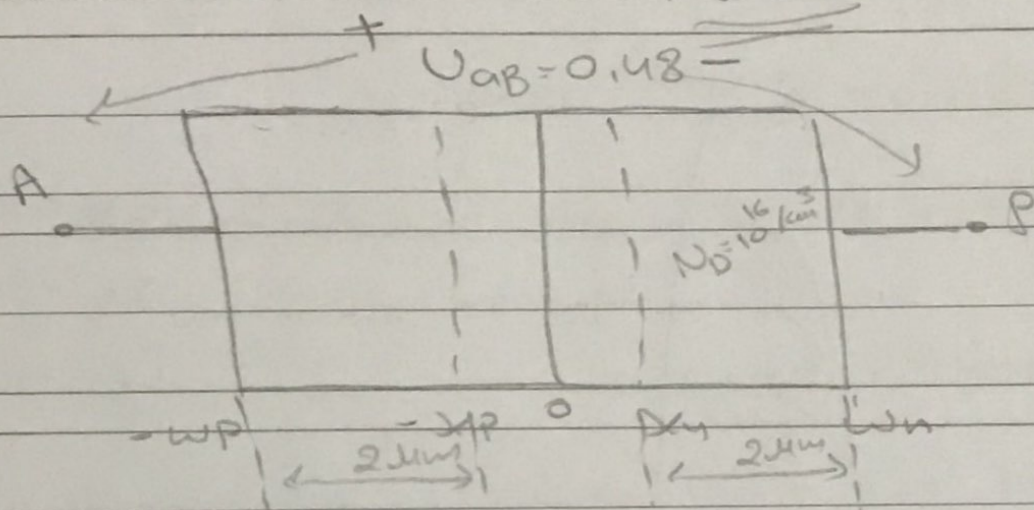
Subject: _____

PS #4

forward biased
 $V_B > 0$

Problem "7"

$$N_D = 10^{16}$$



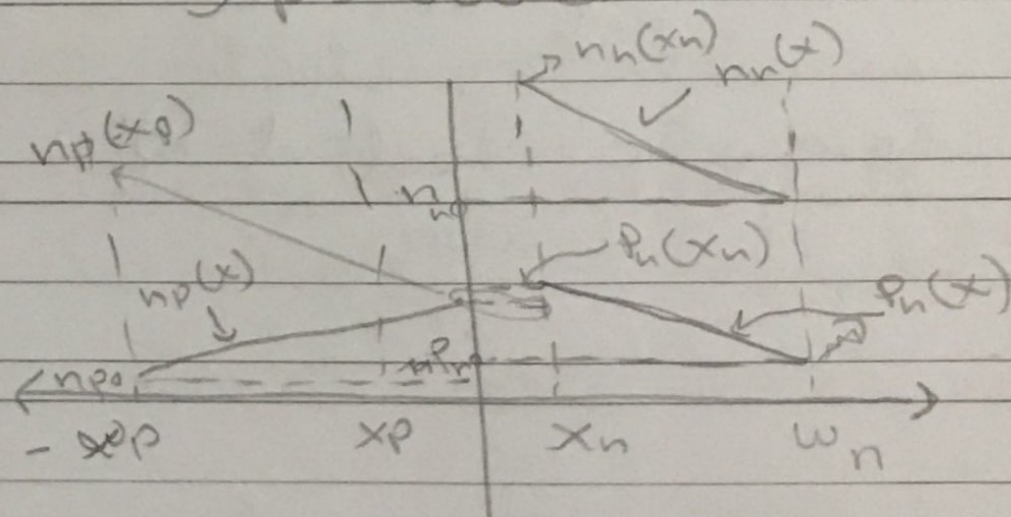
$$\Rightarrow x_p = x_n \approx 0, L \gg 2\mu m \Rightarrow L_p \gg w_n$$

$$L_n \gg w_p$$

\Rightarrow it is a short circuit diode

$$\mu_n = 1600 \text{ cm}^2/\text{V}\cdot\text{s}$$

$$\mu_p = 600 \text{ cm}^2/\text{V}\cdot\text{s}$$



$$a // (i) P_n(w_n) = P_{n0} = \frac{n_i^2}{N_D} = \frac{2.25 \times 10^{20}}{10^{16}}$$

$$= 2.25 \times 10^4 \text{ holes/cm}^3$$

$$(ii) P_n(x_n) = P_{n0} e^{V_D/V_T} = 2.25 \times 10^4 e^{480/25}$$

$$\left. \begin{aligned} P_n(x) &= P_{n0} + P'_n(x) \\ n_n(x) &= n_{n0} + n'_n(x) \end{aligned} \right\} P'_n(x) = n'_n(x)$$

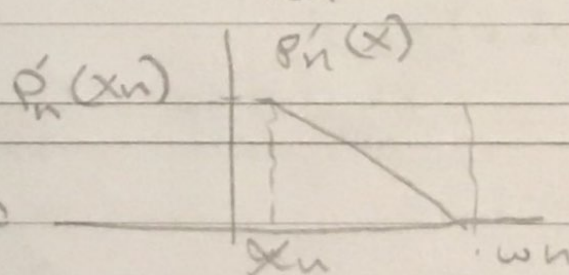
$$(iii) P_p(x) = q P'_n(x) \rightarrow Q_p = \int_{x_n}^{w_n} P_p(x) dV$$

$$= \int_{x_p}^{w_n} P_p(x) A dx = Aq \int_{x_n}^{w_n} P'_n(x) dx$$

$$Q_p = q A P'_n(x_n) \frac{w_n - x_n}{2}$$

$$= q A P'_n(x_n) \frac{w_n}{2} \rightarrow \text{40 Lms (Ans)}$$

$$= 3.488 \text{ fC}$$



$$\text{iv) } J_p(0) = J_p(x_n) = -q D_p \frac{d}{dx} (P_n(x))$$

$$= -q D_p \frac{d}{dx} (P'_n(x)) \approx 0$$

$$= -q D_p \frac{P'_n(w_n) - P'_n(x_n)}{w_n - x_n} \approx 0$$

$$= \frac{q D_p P'_n(x_n)}{w_n} = 26.16 \text{ mA/cm}^2$$

$$\textcircled{B} \quad n_p(-x_p) = P_n(x_n) / 10$$

(i)

$$n_p(-x_p) = n_{p0} e^{u_0/u_T} \Rightarrow n_{p0} = n_p(-x_p) e^{-u_0/u_T}$$

$$= \frac{P_n(x_n)}{10} e^{-u_0/u_T} = 2.18 \times 10^6 e^{-\frac{40}{25}} \approx 10^3 / \text{cm}^3$$

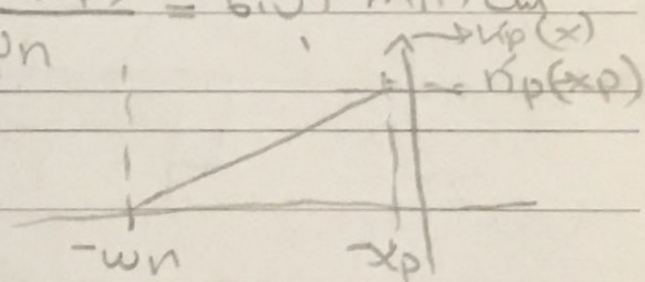
$$\Rightarrow N_A = n_i^2 / n_{p0} = 2.25 \times 10^{17} / \text{cm}^3$$

$$(ii) Q_n' = q A n_p' (-x_p) \frac{w_n}{2} = 0.3488 \text{ fC}$$

$$(iii) J_n(0) = J_n(-x_p) = q D_n \frac{dn_p(x)}{dx} = q D_n \frac{dn_p(x)}{dx}$$

$$\dot{I} = q D_n \frac{n_p'(-x_p) - n_p'(-w_n)}{-x_p - (-w_n)}$$

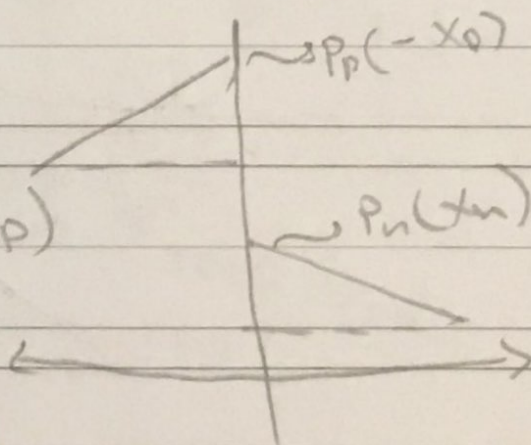
$$= q D_n \frac{n_p'(-x_p)}{w_n} = 6.97 \text{ mA/cm}^2$$



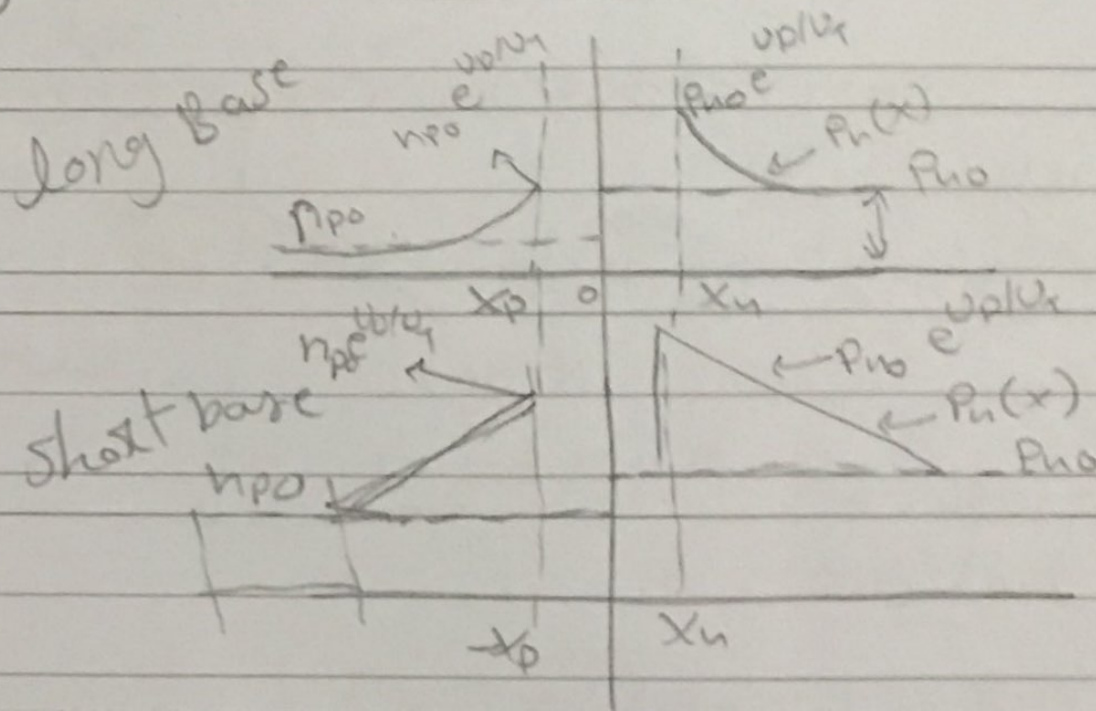
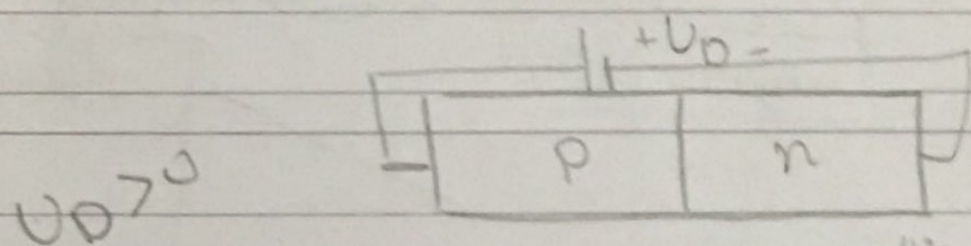
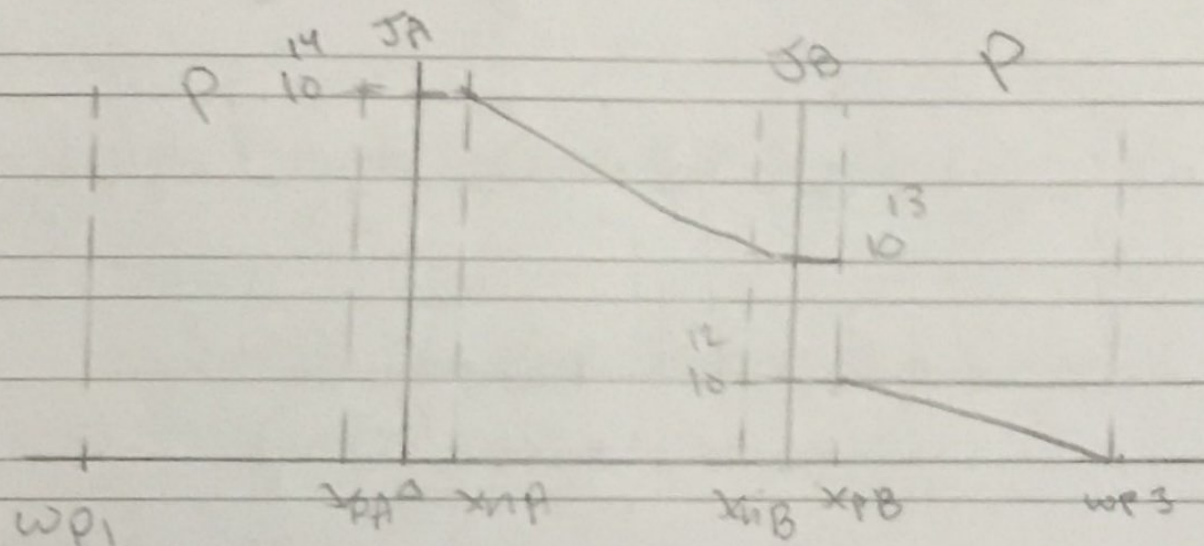
(iv)

$$\phi = V_T \ln \frac{P_n(x_n)}{P_p(-x_p)}$$

$$P_p(-x_p)$$



Problem (8) :-



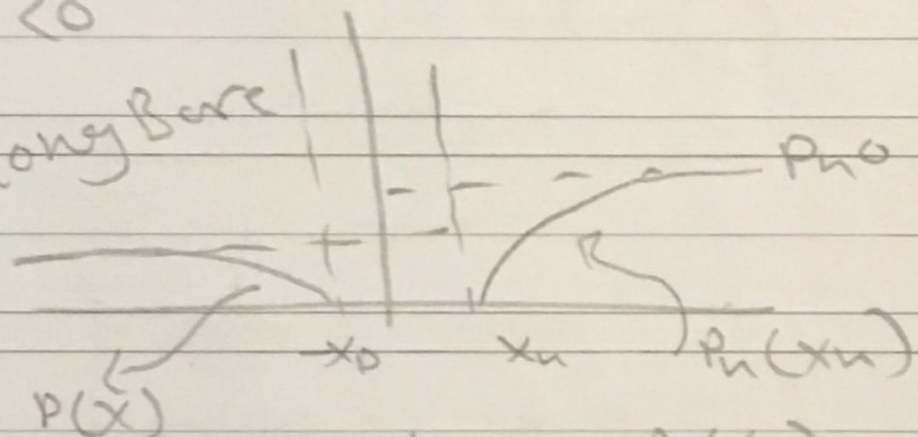
لما تزيد كمان في junction forward bias
reverse bias

$$P'_n(x_{nB}) = P_{n0} e^{V_{DB}/V_T} - P_{n0} = 10^{13}$$

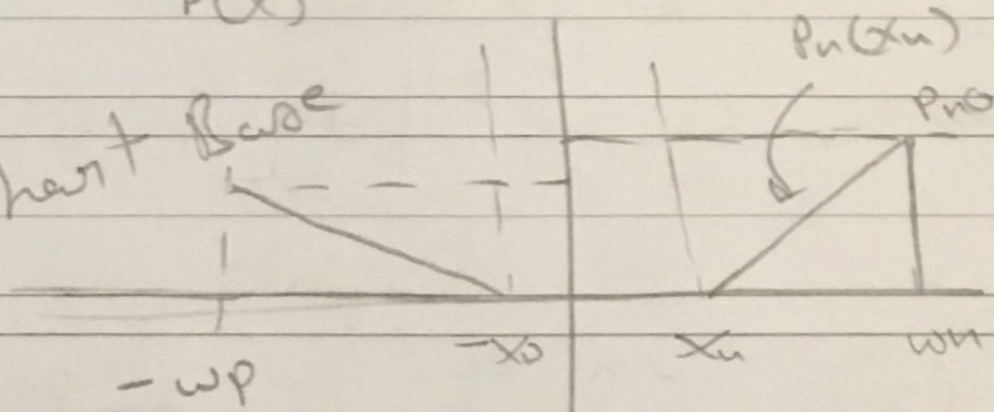
$$P'_n(x_{nA}) = P_{n0} e^{V_{DA}/V_T} - P_{n0} = 10^{14}$$

$V_D < 0$

long Base



short Base

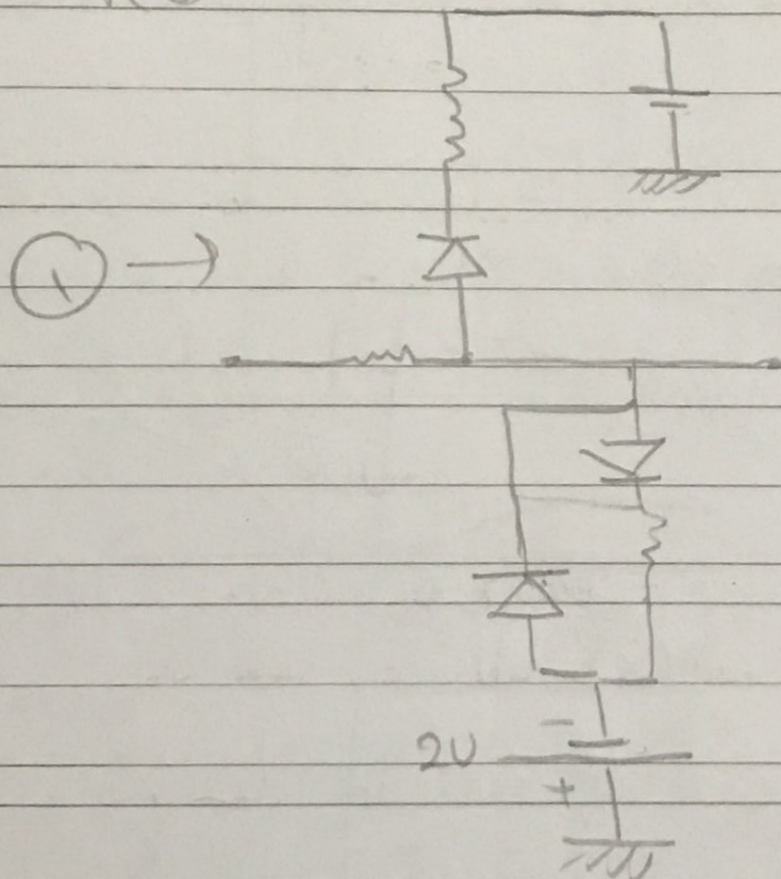


Subject: _____

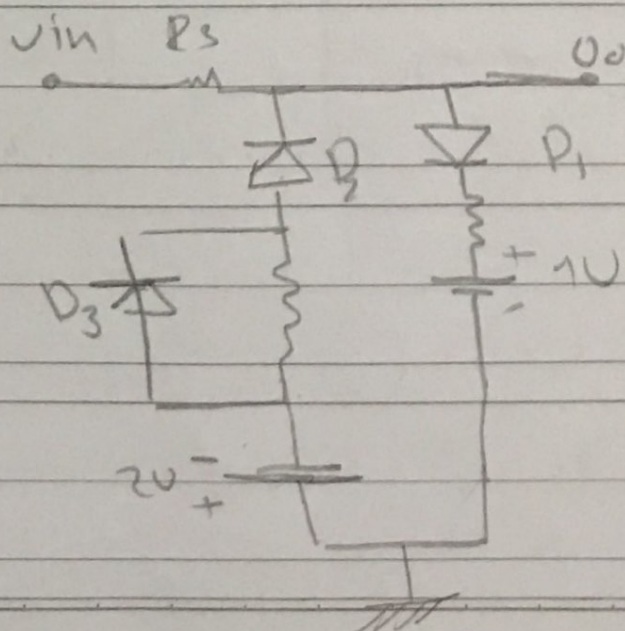
/ /

PS#5

P(9)



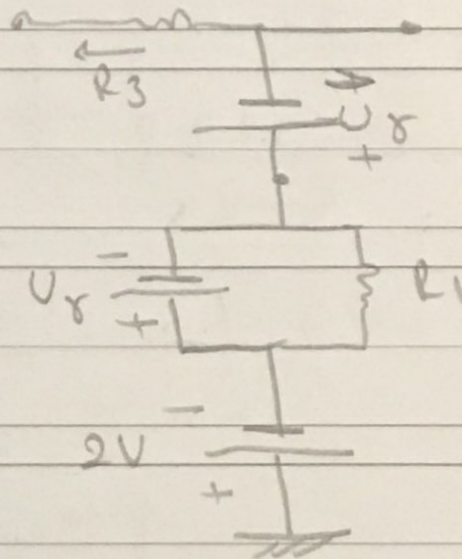
②



Subject: _____

/ /

when D_1 off, D_2 & D_3 on



$$U_o = -2U_x = -3.4V$$

for $U_o \geq U_{in} \Rightarrow$ for $U_{in} \leq -3.4V$

$$I = \frac{U_x}{R_1} \leftarrow U_{open} \leftarrow \text{جهد المفتوح}$$

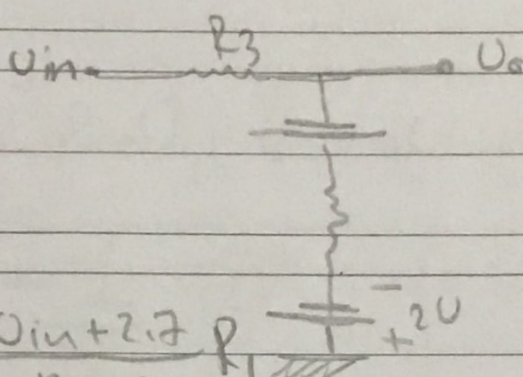
$$\frac{-3.4 - U_{in}}{R_3} = \frac{U_x}{R_1}$$

$$-3.4 - U_{in} = \frac{U_x R_3}{R_1}$$

$$U_{in} = -3.4 - \frac{U_x R_3}{R_1}$$

Subject: _____

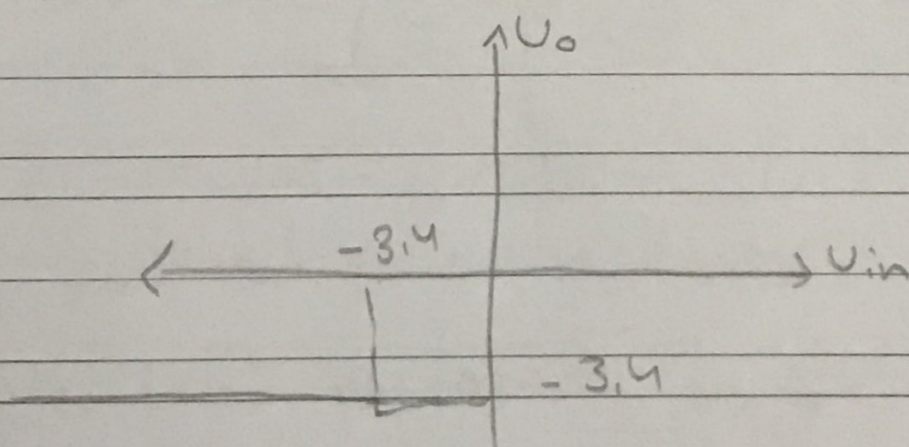
/ /



$$U_{in} = -3.4$$

$$U_o = -2.7 + \frac{U_{in} + 2.7}{R_1 + R_3} R_1$$

$$= -2.7 + \frac{(-3.4 + 2.7)}{4} R_1$$



Subject: _____

/ /

clipping	دائرة القص
clamping	دائرة السبك

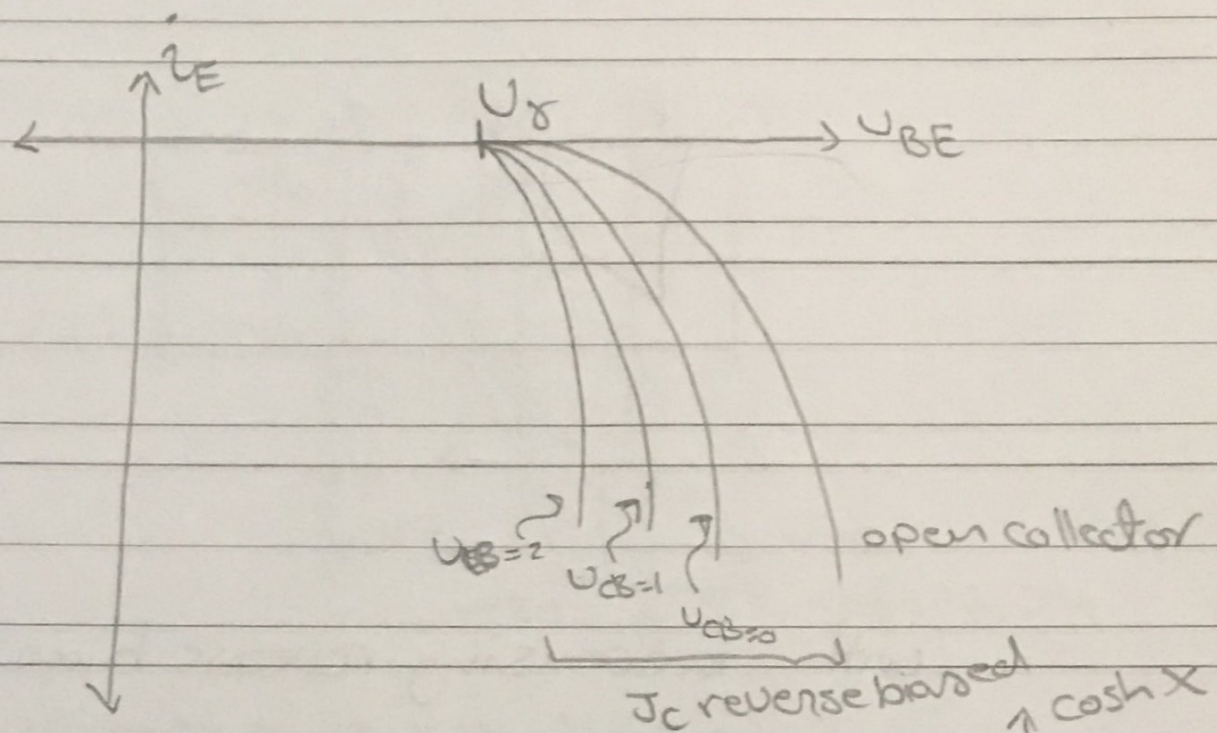
23/5/2017

* The input characteristics :-

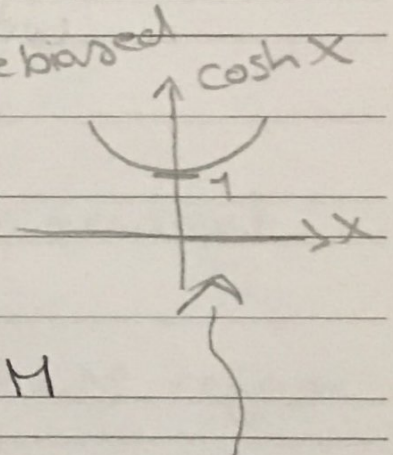
Plot of I_E versus V_{BE} for different values of V_{CB}

⇒ it is the characteristic of Base-Emitter diode at different base collector voltages

$|I_E|$ increases as the reverse bias of the collector junction increased



- why?



1. we know that $\alpha_F = \beta \alpha_T M$

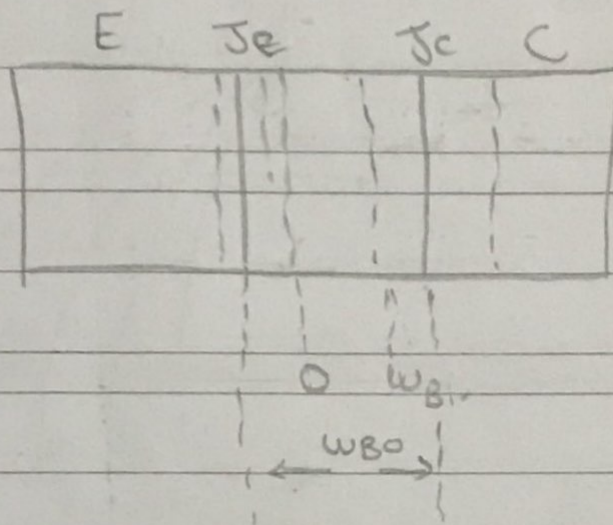
$\alpha_T =$ base Transmission factor $= \frac{1}{\cosh(w_B/L_B)}$

$w_B \triangleq$ effective Base width

$L_B \triangleq$ Diffusion length of minority carriers in base region E&C have higher doping level than B.

Subject: _____

Short Base straight line



with increasing reverse bias of J_C

\Rightarrow base width (w_B) increases

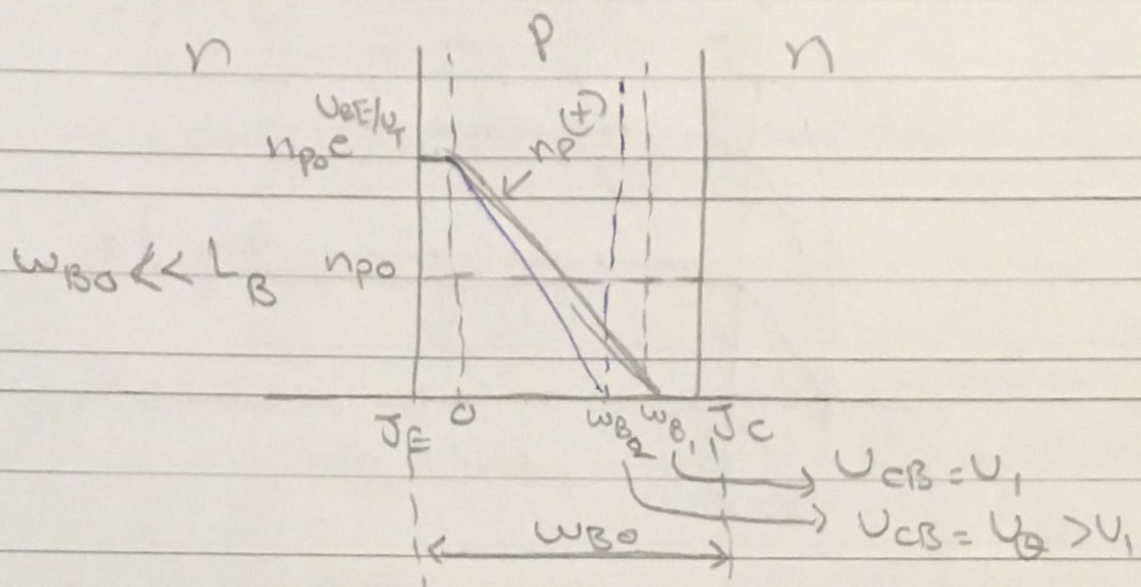
$\Rightarrow \alpha_T$ increases

$\Rightarrow \alpha_F$ increases

\Rightarrow magnitude of I_E slightly increases with increasing reverse bias of J_C

2 - concentration gradient of minority

carriers in base region



- increasing reverse bias of J_C

\Rightarrow magnitude of concentration gradient

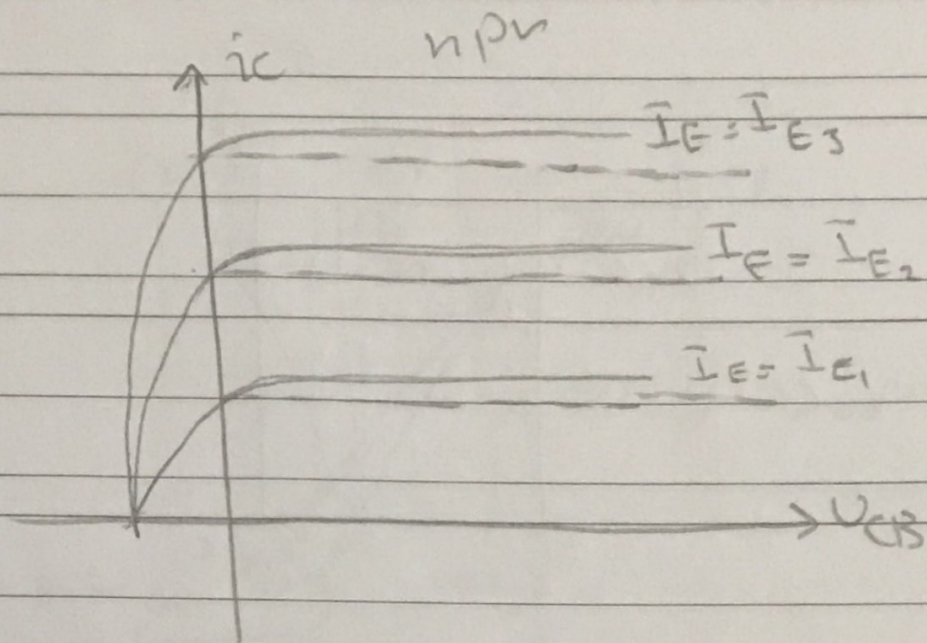
of minority carriers in base region
increases

\Rightarrow diffusion current increases with
creasing reverse bias of J_C

$\Rightarrow I_E$ increases with increasing
reverse bias of J_C

Subject: _____

/ /



$$|I_{E3}| > |I_{E2}| > |I_{E1}|, I_{E1} < 0, I_{E2} < 0, I_{E3} < 0$$

The Effective base width of the base is given by :-

$$W_B = W_{B0} - \left[\frac{qE}{qN_B} (\phi_{oc} - V_{BC}) \right]$$

for npn
for pnp

N_B = Base doping level

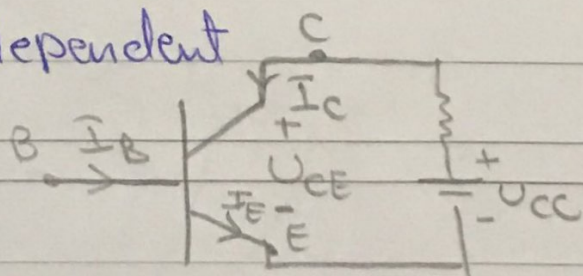
The punch Through voltage V_{PT} is value of V_{CB} reverse bias that reduces Effective base width

W_B to zero causing Breakdown of
BJT

$$W_B = W_{B0} - \left[\frac{2E}{qN_B} (\phi_{oc} + V_{RT}) \right]$$

- Common Emitter characteristics -

- V_B & V_{CE} are the independent
values

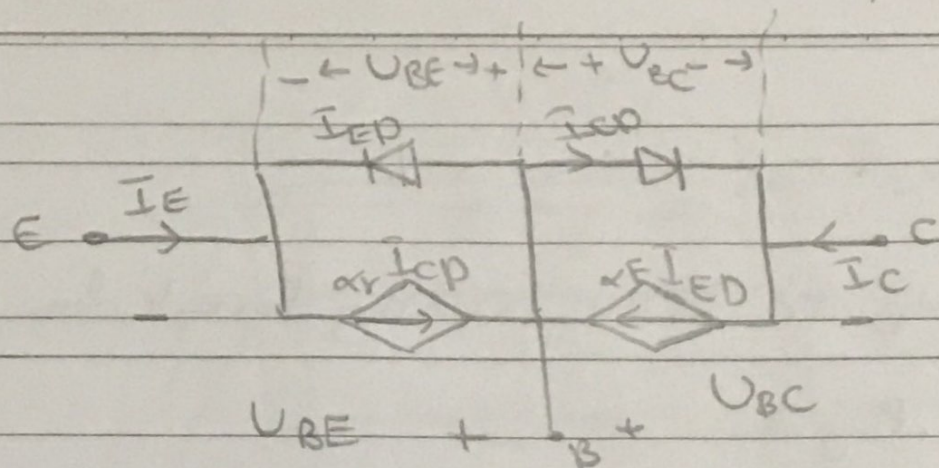


- I_C , V_{BE} are the dependent values

$$I_C = f_1(I_B, V_{CE}), V_{BE} = f_2(I_B, V_{CE})$$

$$V_{CE} = V_{CB} + V_{BE} = V_{BE} - V_{BC} \\ = V_{BE} -$$

Subject: _____



with J_E P.b & J_C R.b

$$\Rightarrow I_E = -I_{ED}, I_C = \alpha_F I_{ED} = -\alpha_F I_E$$

$$I_B = -(I_C + I_E) = -(1 - \alpha_F) I_E$$

$$I_E = \frac{1}{1 - \alpha_F} I_B, I_C = -\alpha_F I_E + I_{CO}$$

$$\therefore I_C = -\alpha_F I_E + I_{CO}$$

$$= -\alpha_F [-(I_B + I_C)] + I_{CO}$$

$$I_C = \alpha_F (I_B + I_C) + I_{CO}$$

$$I_C (1 - \alpha_F) = \alpha_F I_B + I_{CO}$$

$$I_C = \underbrace{\frac{\alpha_F}{1 - \alpha_F}}_{\beta_F} I_B + \frac{1}{1 - \alpha_F} I_{CO} = \beta_F I_B + (1 + \beta_F) I_{CO}$$

في نظام الترددات المنخفضة
 \rightarrow

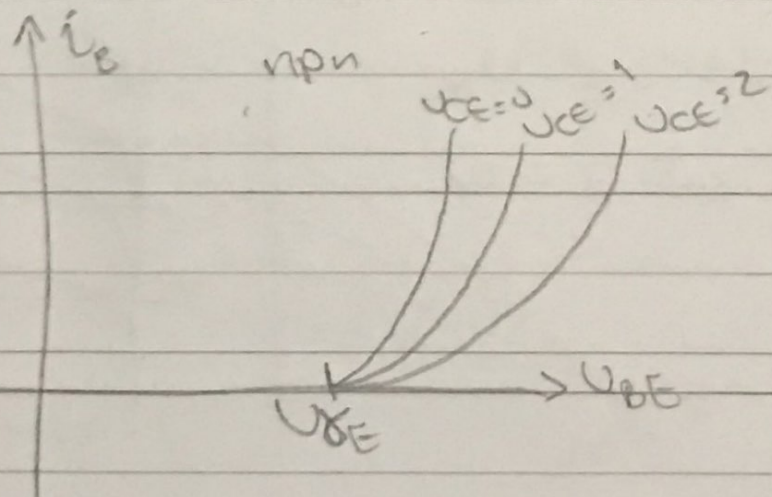
$$I_C = \beta_F I_B + (1 + \beta_F) I_{C0}$$

The dc forward current gain is defined

$$h_{FE} \triangleq \frac{I_C}{I_B} \cong \beta_F$$

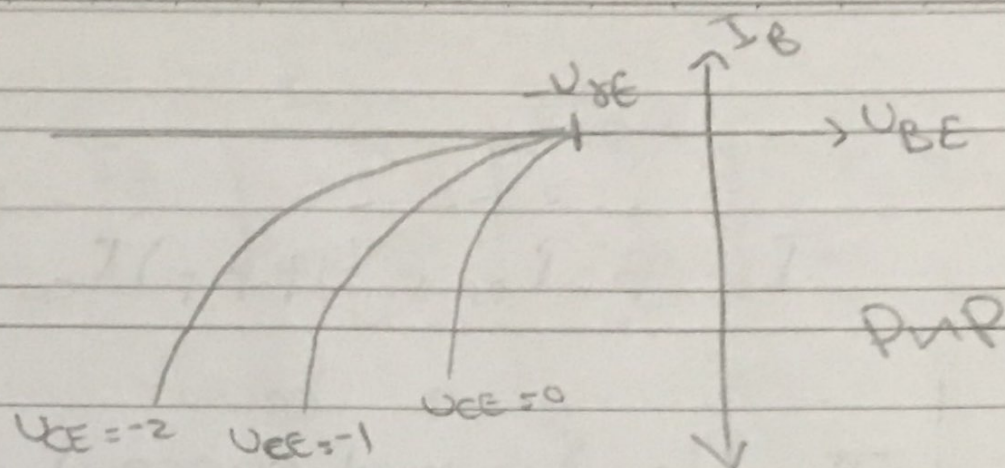
CE input characteristics :-

I_B vs. V_{BE} for different V_{CE}



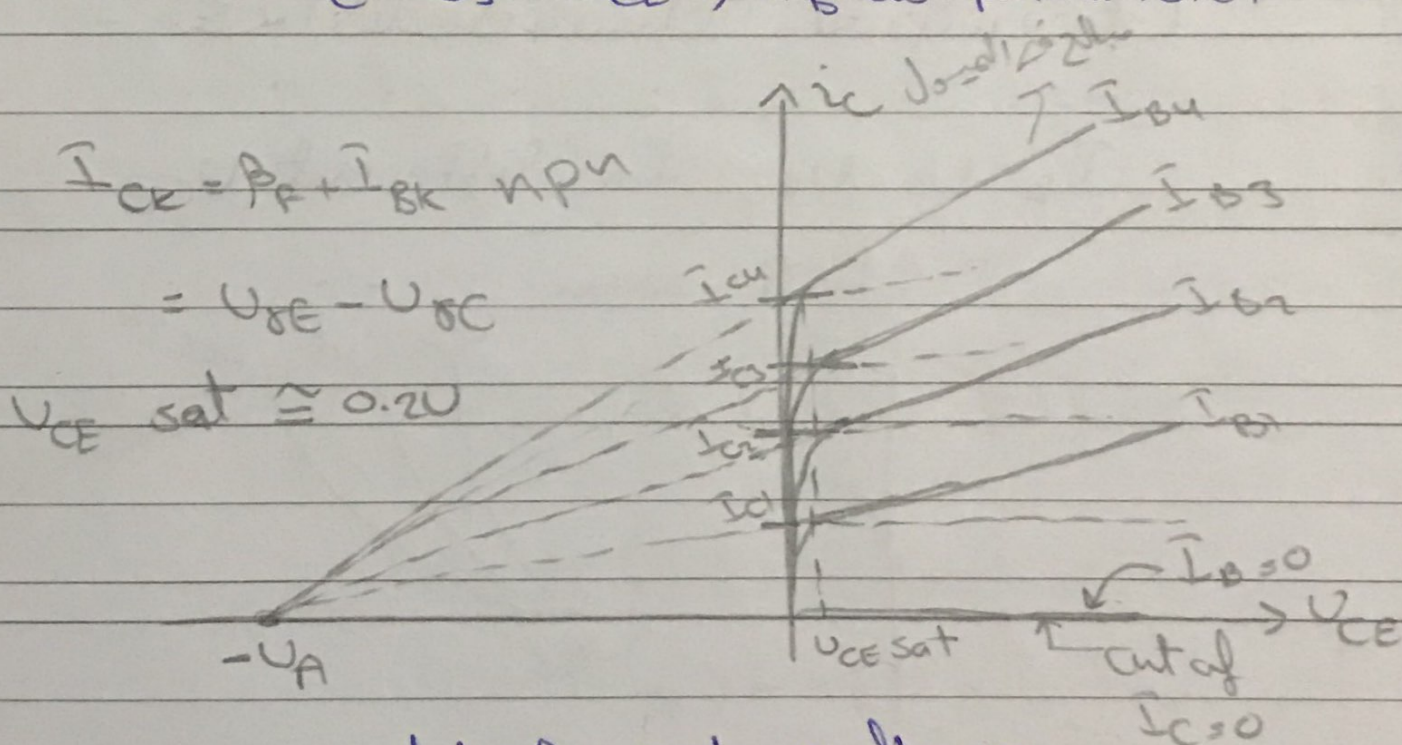
لناتىيو V_{CE} بعاها نرىو فى الافيا؛ العكس

Subject: _____



CE output characteristics \rightarrow

I_C vs V_{CE} , I_B as parameter



$$I_{CE} = \beta_F I_{BK} \text{ PNP}$$

$$= V_{BE} - V_{BC}$$

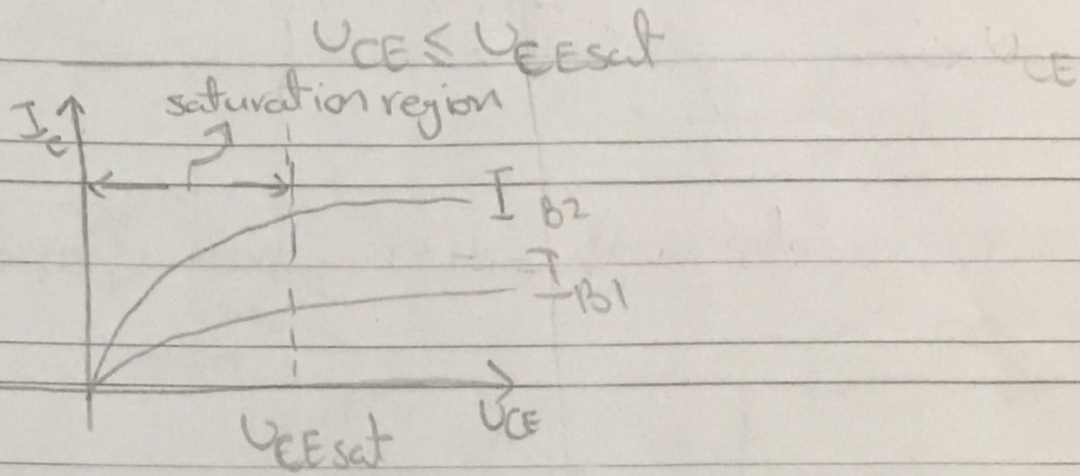
$$V_{CE sat} \approx 0.2V$$

$V_A \triangleq$ early voltage

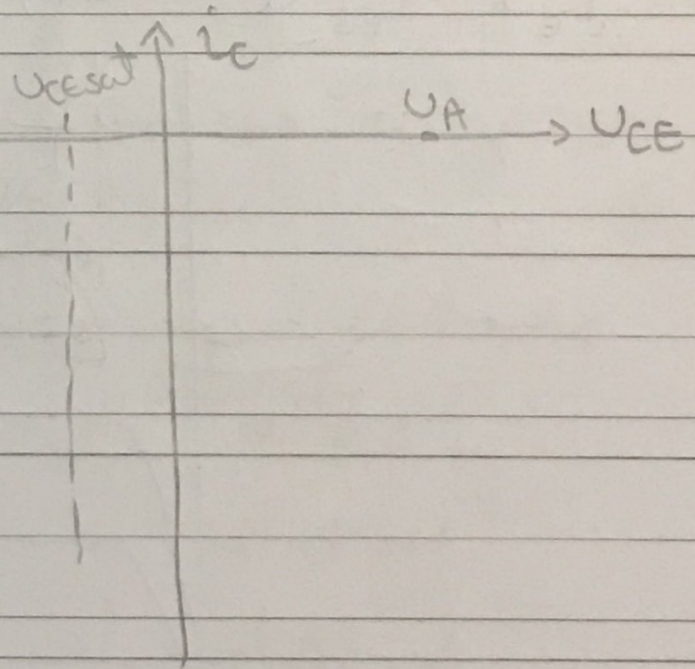
+ve slope of curves due to base width modulation

Subject: _____

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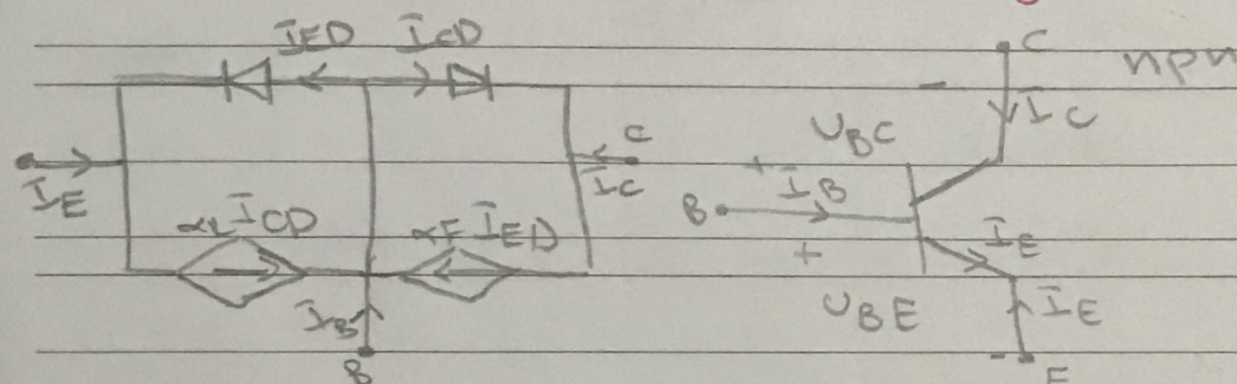


* مبالغ في الميول لأن V_A تكون كبيرة جداً
أي أن الميول بسيط جداً (تقارباً من خط مستقيم)



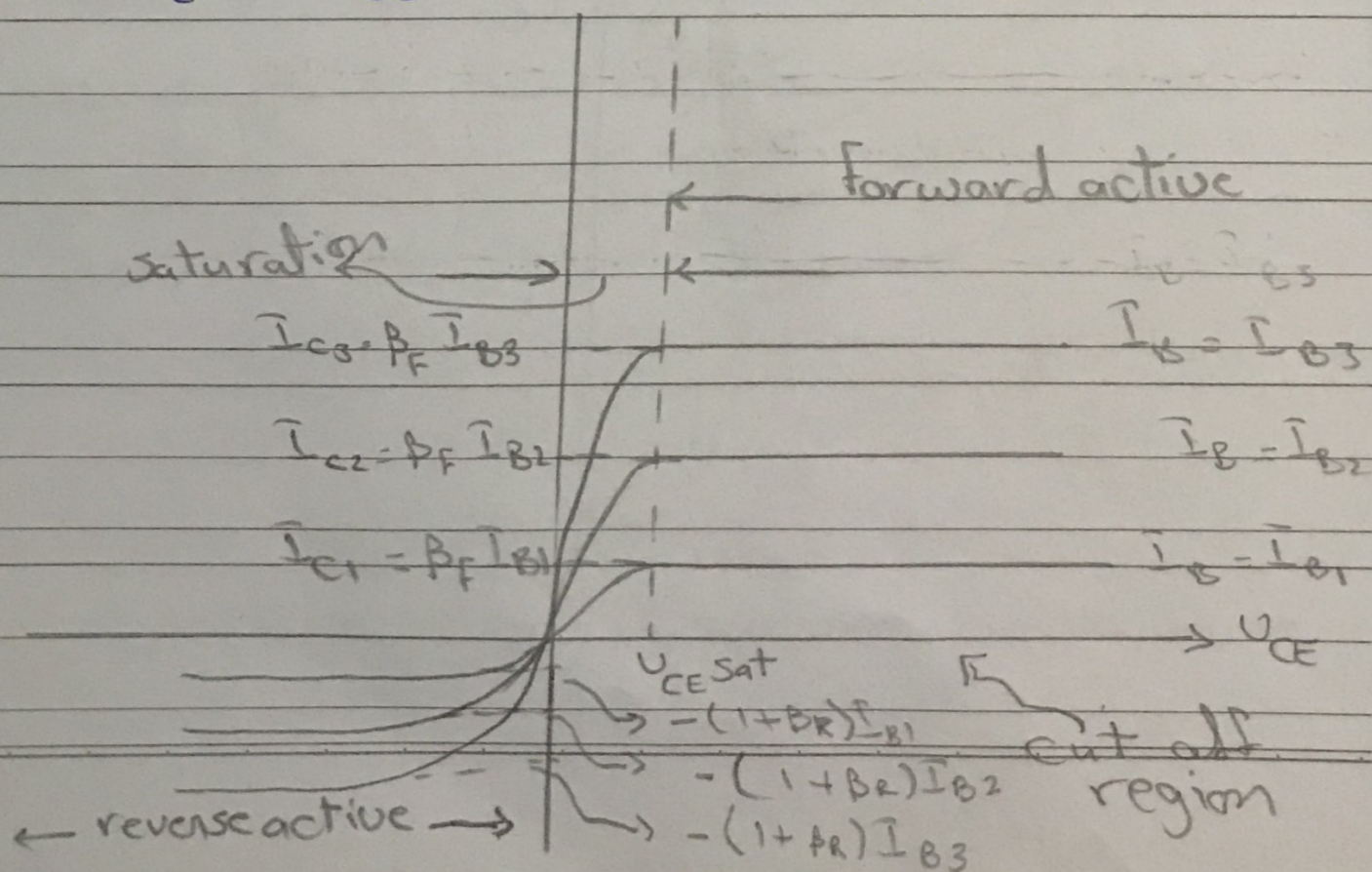
2017/5/30

BJT models in the 4-regions of operation

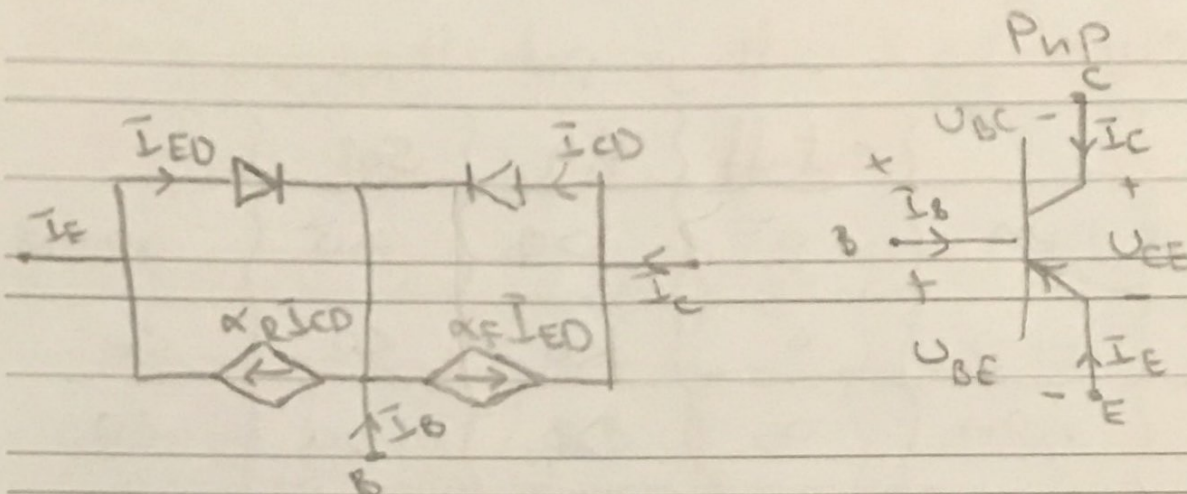


$$I_C = -I_{CS} (e^{V_{BC}/U_T} - 1) + \alpha_F \bar{I}_{ES} (e^{V_{BE}/U_T} - 1)$$

$$I_E = -\bar{I}_{ES} (e^{V_{BE}/U_T} - 1) + \alpha_R I_{CS} (e^{V_{BC}/U_T} - 1)$$

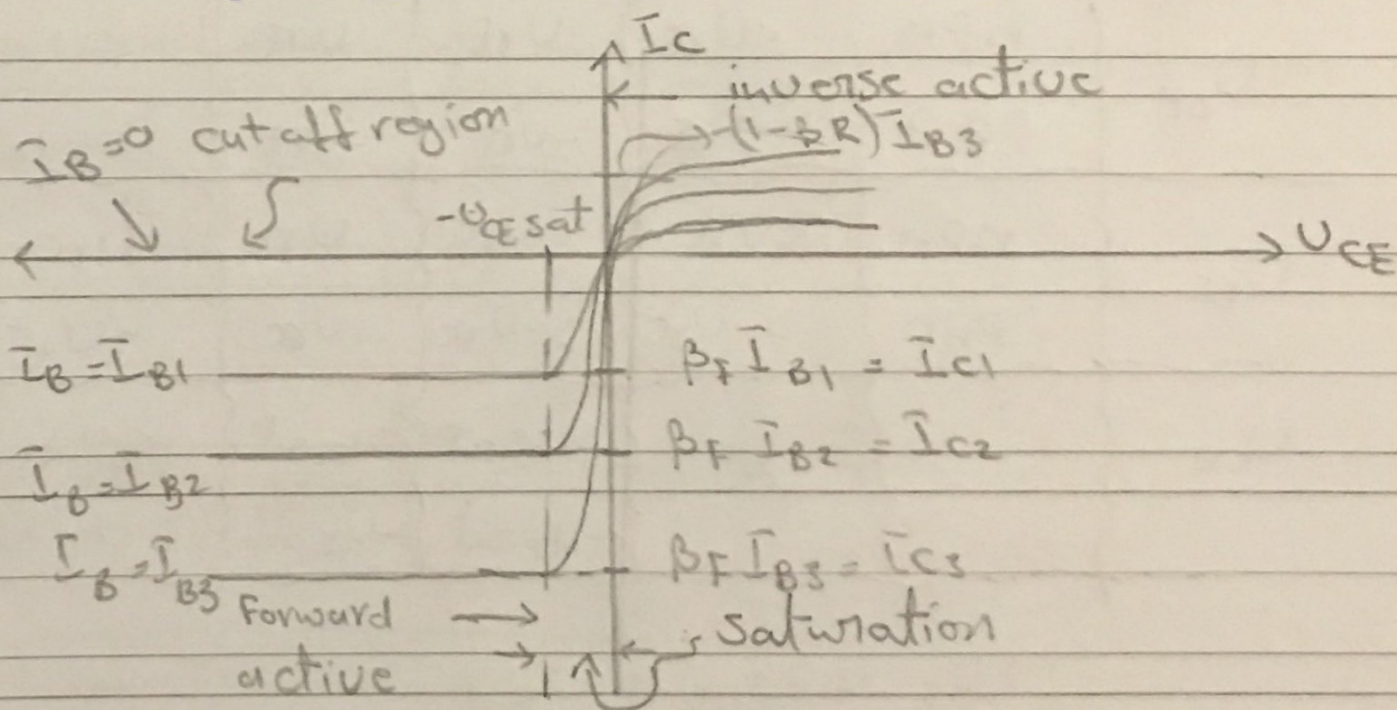


Subject: _____



$$\bar{I}_C = \bar{I}_{ES} (e^{-U_{BC}/U_T} - 1) - \alpha_F \bar{I}_{ES} (e^{U_{BE}/U_T} - 1)$$

$$\bar{I}_E = \bar{I}_{ES} (e^{U_{BE}/U_T} - 1) - \alpha_R \bar{I}_{ES} (e^{-U_{BC}/U_T} - 1)$$



* Currents & Voltage polarities

inverse
active

		cut off	F.A	Sat	I.A
I_B	nPN	0	>0	>0	>0
	PnP	0	<0	<0	<0
I_C	nPN	0	>0	>0	<0
	PnP	0	<0	<0	>0
I_E	nPN	0	<0	<0	>0
	PnP	0	>0	>0	<0
U_{BE}	nPN	$<U_{BE}$	U_{BE}	U_{BE}	$<U_{BE}$
	PnP	$>-U_{BE}$	$-U_{BE}$	$-U_{BE}$	$>-U_{BE}$
U_{BC}	nPN	$<U_{BC}$	$<U_{BC}$	U_{BC}	U_{BC}
	PnP	$>-U_{BC}$	$>-U_{BC}$	$-U_{BC}$	$-U_{BC}$
U_{CE}			$>U_{CEsat}$	U_{CEsat}	$<-U_{CEsat}$
			$<-U_{CEsat}$	$-U_{CEsat}$	$>U_{CEsat}$

$$U_{CE} = U_{CB} + U_{BE}$$

$$= U_{BE} - U_{BC}$$

$$U_{CEsat} = U_{BE} - U_{BC} = 0.7 - 0.5 = 0.2 \text{ V (Si)}$$

$$I_E = -(I_C + I_B)$$

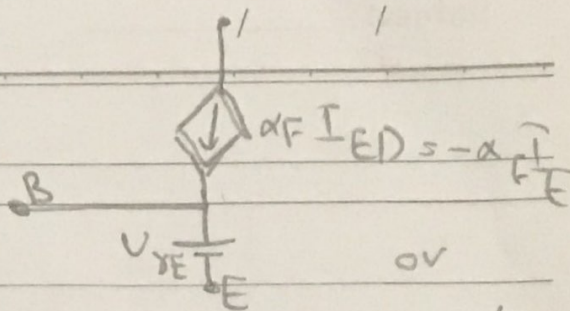
كل التيار يخرج من القاعدة

$$U_{CE} = U_{CB} + U_{BE} = -U_{BC} + U_{BE} = -U_{BC} + U_{BC}$$

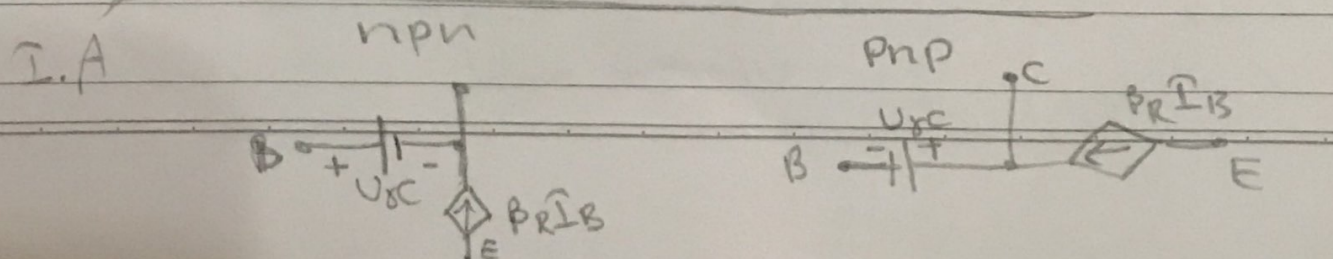
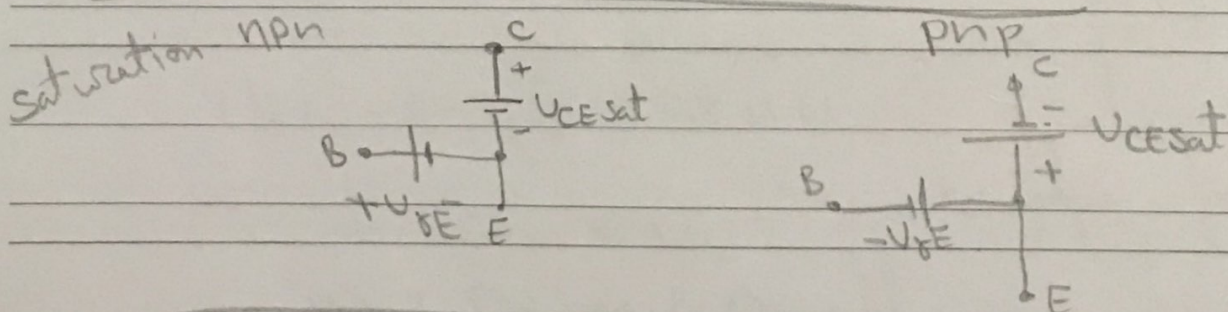
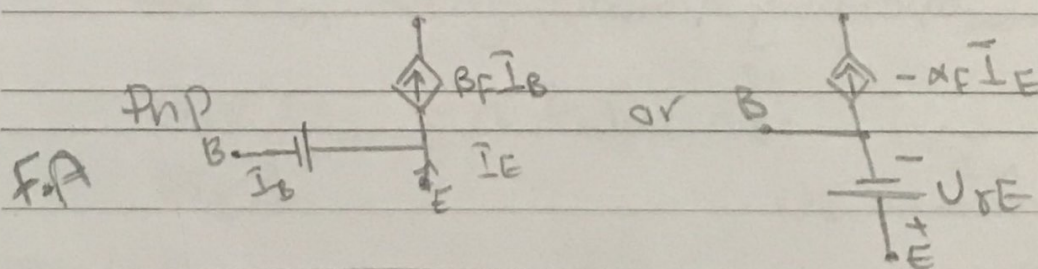
$$U_{BE} < U_{BC} \Rightarrow U_{CE} < U_{BE} - U_{BC} < U_{CEsat}$$

Subject: _____

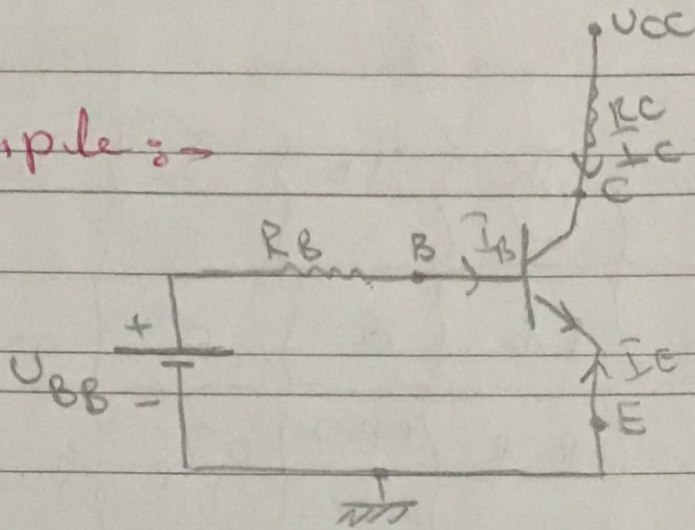
models



Region	I_E	I_C	I_B	I_C	I_E	model
cutoff	R.B	R.B	0	0	0	
F.A	F.B	R.B	nnp > 0 pnp < 0	$\beta_F \bar{I}_B$ independent I_{CE}	$-(1+\beta_F) \bar{I}_B$	
saturation	F.B	F.B	nnp > 0 pnp < 0	?	$-(I_C + I_B)$	
Inverse active	R.B	F.B	nnp > 0 pnp < 0	$\beta_R \bar{I}_B$		



Example: \rightarrow



Let $R_B = 100k\Omega$, $R_C = 4k\Omega$, $V_{CC} = 10V$

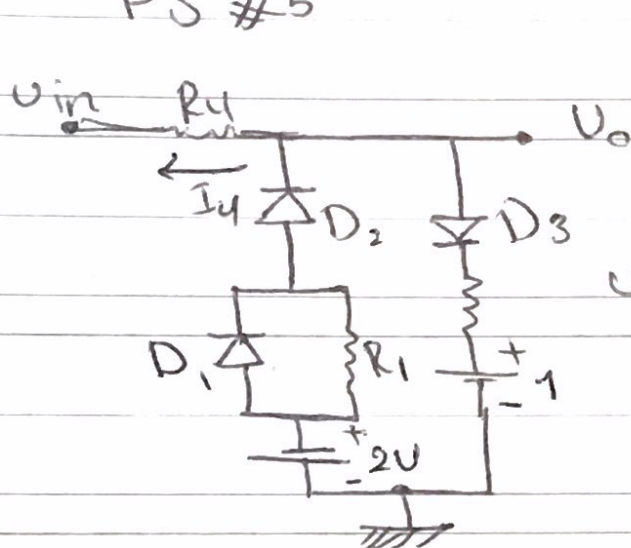
$$U_{BE} = 0.7V, U_{CE} = 0.5V$$

$$\beta_F = 100, \beta_R = 1$$

a) for $U_{BB} = 1.7V$ Determine the operating point

Tutorial

PS #5



$$V_g = 0.7V$$

for V_{in} very -ve

D_1 & D_2 on & D_3 off

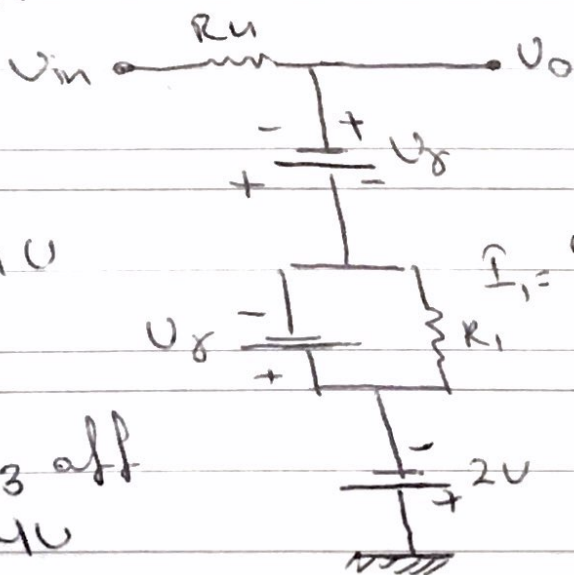
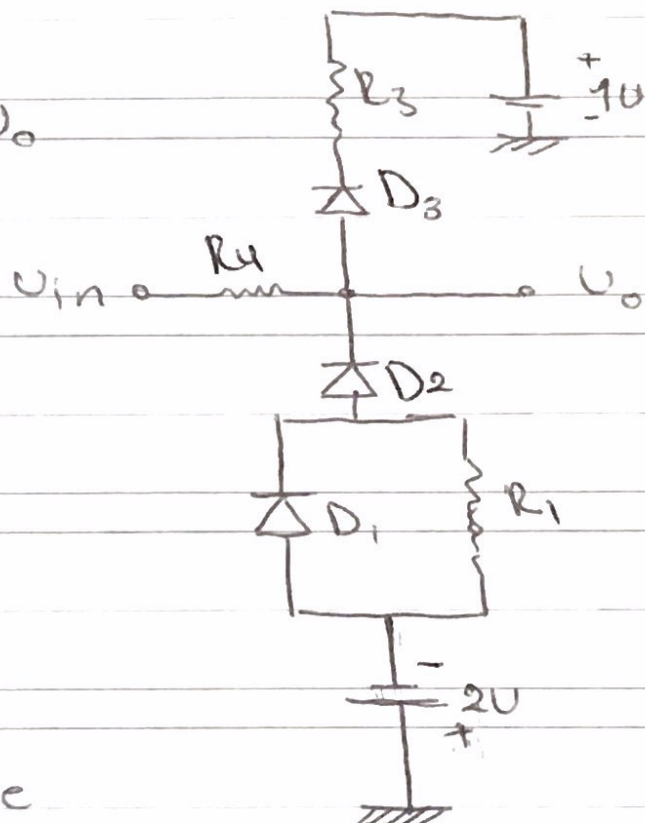
~~D_3~~

$$V_o = -2 - 2V_g = -3.4V$$

for $V_{in} \leq V_1$

D_1 & D_2 on & D_3 off

$$V_o = -3.4V$$



- find V_1 :- @ $V_{in} = V_1 \Rightarrow \hat{I}_{D1} = 0$

$$\hat{I}_4 = \hat{I}_{D2}, \hat{I}_{D2} = \hat{I}_{D1} + \hat{I}_1$$

$$\hat{I}_4 = \frac{V_0 - V_{in}}{R_4} = \frac{-3.4 - V_{in}}{R_4} \text{ for } V_{in} < V_1$$

$$V_{in} \uparrow \Rightarrow \hat{I}_4 \downarrow \Rightarrow \hat{I}_{D2} \downarrow \Rightarrow \hat{I}_{D1} \downarrow$$

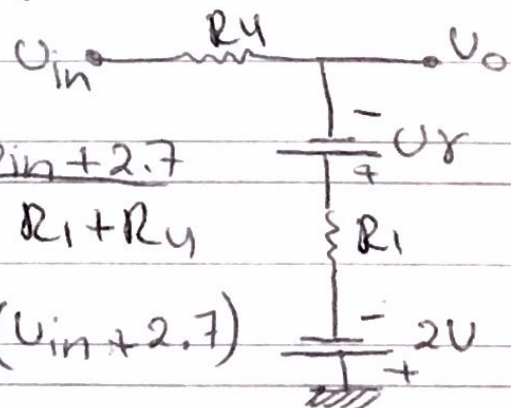
$$\hat{I}_4 = \hat{I}_{D2} = \hat{I}_1 = \frac{V_x}{R_1}$$

$$V_{in} = V_0 - R_4 \hat{I}_4 = -3.4 - \frac{R_4}{R_1} V_x = -5.5 V$$

- for $V_1 < V_{in} < V_2$

D_1 off, D_3 off, D_2 on

$$\begin{aligned} V_0 &= -2.7 + R_1 \frac{V_{in} + 2.7}{R_1 + R_4} \\ &= -2.7 + \frac{1}{4} (V_{in} + 2.7) \\ &= \frac{1}{4} V_{in} - \frac{8.1}{4} = \frac{V_{in}}{4} - 2.025 \end{aligned}$$



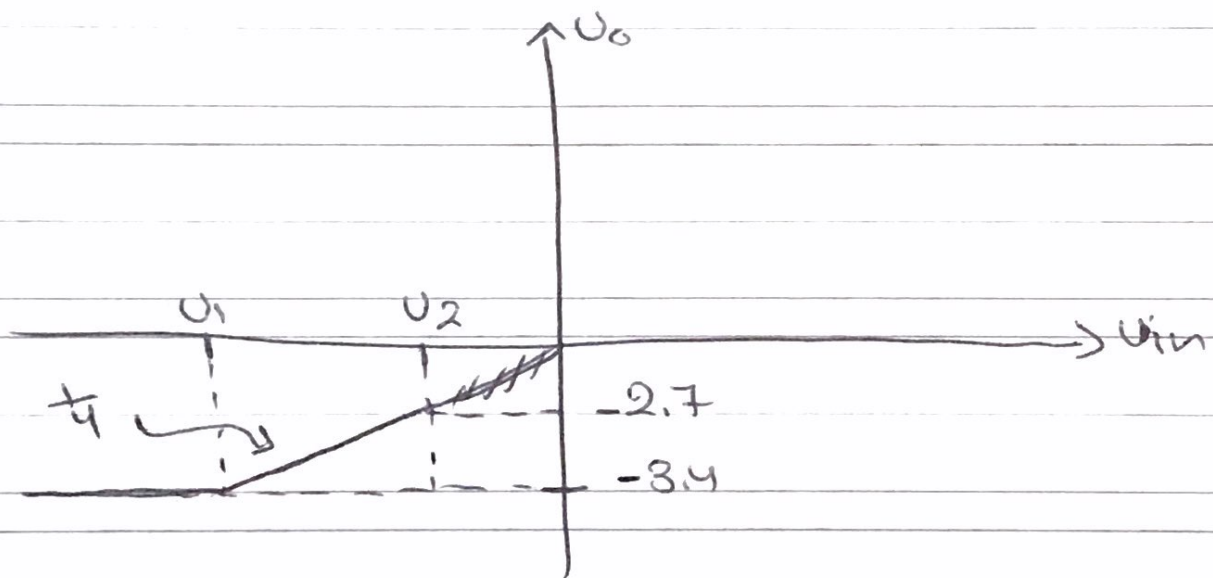
when D_2 Turns off

⑨ $\underline{V_{in}} = -V_2, D_3$

$$V_o I_u = \frac{-2.7 - V_{in}}{R_1 + R_u} = I_{D2}$$

I_{D2} on for $V_{in} < -2.4$

for $V_{in} \geq -2.7$, D_2 off



$$U_2 = -2.7$$

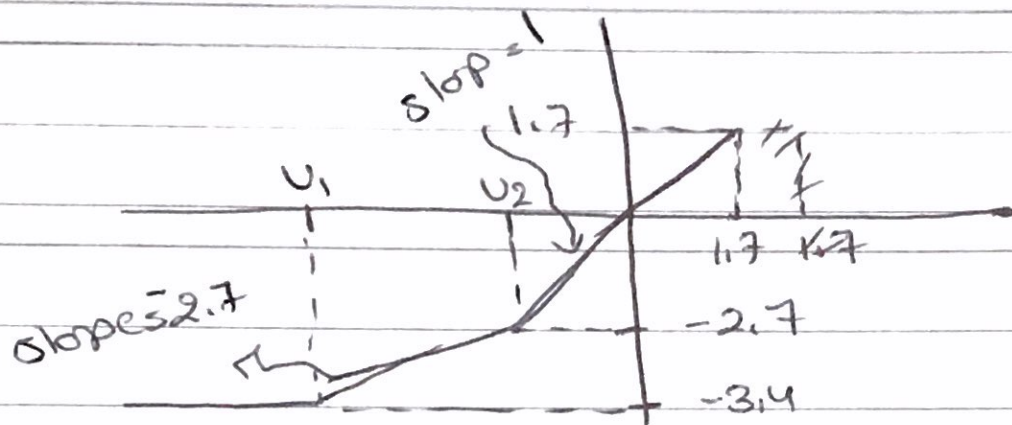
⑩ $V_{in} = U_2 \Rightarrow V_o = \frac{-2.7}{4} - \frac{3}{4}(2.7)$

for $U_2 < V_{in} < U_3$ $= -2.7$

D_1, D_2 & D_3 off

$$V_o = V_{in}$$





② $U_{in} = U_3$, D_3 Turns on

$$U_0 = 1.7 \text{ (since } U_3 = 1.7 \text{)}$$

$$U_0 = 1 + 6U = 1.7U = U_{in}$$

$$\therefore U_3 = 1.7$$

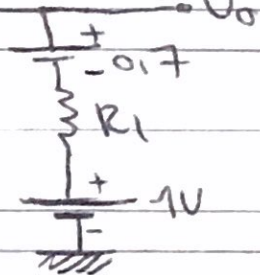
③ for $U_{in} > U_3$, D_1, D_2 off, D_3 on

$$U_0 = 1.7 + \frac{R_1}{R_1 + R_4} (U_{in} - 1.7)$$

$$= 1.7 + \frac{1}{4} (U_{in} - 1.7)$$

$$= \frac{1}{4} U_{in} + \frac{3}{4} (1.7)$$

$$= \frac{1}{4} U_{in} + \frac{5.1}{4}$$



Subject: _____

/ /

$$U_o = \begin{cases} -3.4 & U_{in} \leq -5.5 \\ \frac{1}{4}U_{in} - \frac{8.1}{4} & -5.5 \leq U_{in} \leq 1.7 \\ U_{in} & -2.7 \leq U_{in} \leq 1.7 \\ \frac{1}{4}U_{in} + \frac{5.1}{4} & U_{in} \geq 1.7 \end{cases}$$

~~✗~~

Test Two :-

~~$\frac{dI_s}{dT} = 0.12 \text{ Is}$, $\frac{dI_D}{dT} = ?$ @ $U_D = 0.7 \text{V}$~~

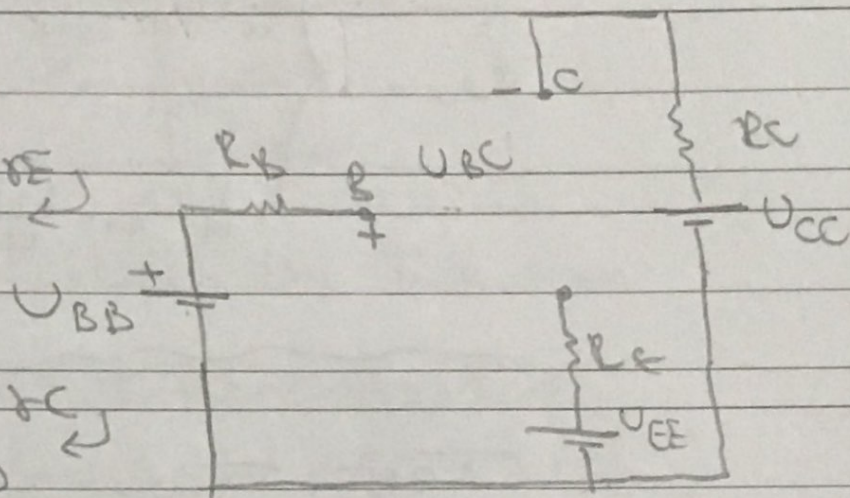
c) if we assume (cut off)

$$V_{BE} = -5.7 < V_{BE}$$

\rightarrow JE is R.b

$$V_{BC} = 3.7 > V_{BC}$$

\Rightarrow JE F.b



\Rightarrow npn is in ~~reverse~~ Active Region

$$\hat{I}_B = \frac{V_{BB} - V_B}{R_B} = \left[\frac{V_{BB} - (V_{BC} - R_C I_C + V_{EE})}{R_B} \right]$$

$$= \left[\frac{(V_{BB} - V_{BC} - V_{EE}) - R_C I_C}{(1 + \beta_R) R_B} \right] / R_B$$

$$\hat{I}_B = \frac{V_{BB} - V_{BC} - V_{EE}}{R_B + (1 + \beta_R) R_C}$$

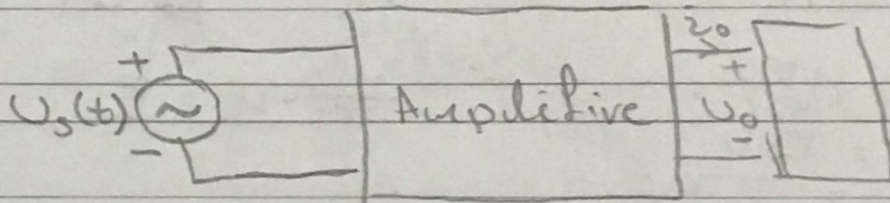
$$= 2.87 \mu A$$

$$I_E = \beta_R I_B = 28.7 \mu A$$

$$I_E = -(1 + \beta_R) I_B = -57.4 \mu A$$

$$V_B = \dots, V_E = \dots, V_C = \dots$$

Example 3 - Transistor as amplifier



مثال رقم 3

The amplifier amplifies the signal $U_s(t)$

$$U_o = A_v U_s(t)$$

\rightarrow Voltage gain

الحالة خطية ونحتاج لنسجل حيث انه يكون
 $I_C = \beta_F I_B$ (forward active) في كسب

$U_s(t)$ - is a small (small amplitude) signal

The amplifire must perserve The shape of the input signal (shape of U_{out} is the same of the shap of $U_s(t)$) and this done by

keeping A_v constant

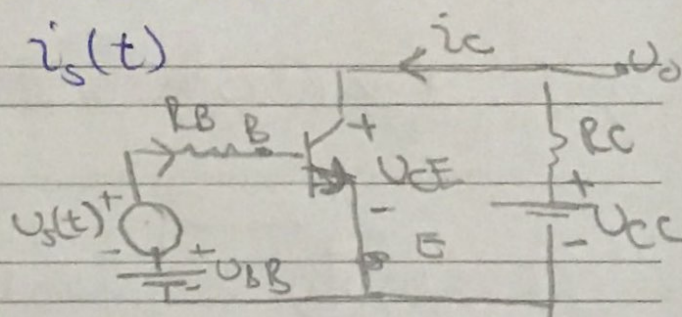
$$-i_o = A_v i_s(t)$$

$$R_B = 100k$$

$$R_C = 4k$$

$$U_{CC} = 12V$$

$$U_{BB} = 1.7V$$

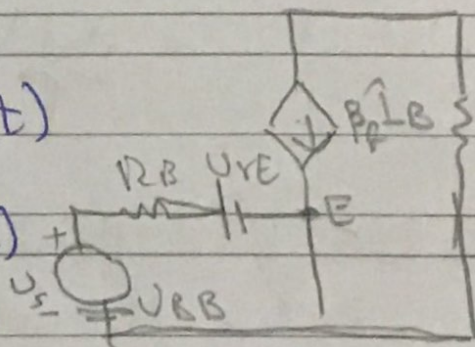


$$\beta_F = 200, \beta_R = 1, U_{BE} = 0.7V$$

$$U_{CE} = 0.5V, U_A = \infty$$

$$I_B = I_{BQ} + i_B(t)$$

$$I_C = I_{CQ} + i_C(t)$$



$$U_{CE} = U_{CEQ} + U_{ce}(t)$$

$\xrightarrow{\text{ac}}$ signal component
 $\xrightarrow{\text{dc}}$ dc component
 $\xrightarrow{\text{instantaneous}}$ instantaneous current

* npn is forward active :-

$$U_S(t) = U_m \sin \omega t \text{ mV}$$

$$U_m = 100$$

$$I_B = \frac{[U_{BB} + U_S(t)] - U_{BE}}{R_B}$$

$$= \frac{U_{BB} - U_{BE}}{R_B} + \frac{U_S(t)}{R_B}$$

$$= I_{BQ} + I_B(t)$$

$$I_{BQ} = 10 \mu A$$

Subject: _____

$$U_o = U_{CE} = U_{CC} - R_C \hat{I}_C$$

$$= U_{CC} - R_C [\hat{I}_{CQ} + i_c(t)]$$

$$= (U_{CC} - R_C \hat{I}_{CQ}) - R_C \hat{I}_c(t)$$

$$= U_{CEQ} + U_{ce}(t)$$

$$U_{CEQ} = U_{CC} - R_C \hat{I}_{CQ}$$

$$= 12 - 4 \times 2 = 4V$$

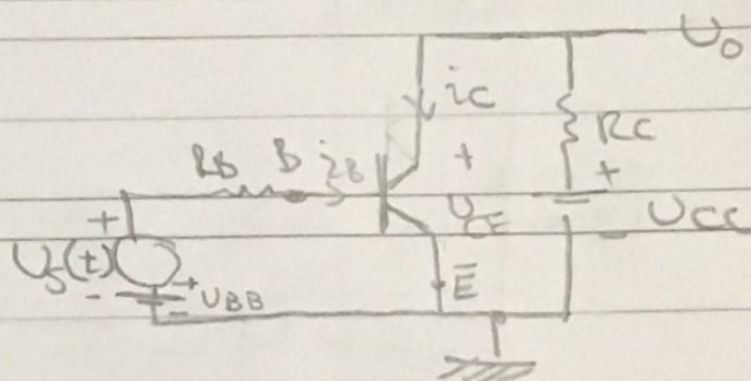
$$U_{ce}(t) = -R_C \hat{I}_c(t) = -4 \times 0.2 \sin \omega t$$

$$= 0.8 \sin \omega t$$

$$\hat{I}_c(t) = \beta_F U_s(t) / R_B$$

$$U_{ce}(t) = -R_C \hat{I}_c(t) = -\beta_F \frac{R_C}{R_B} U_s(t)$$

$$A_v = \frac{U_{ce}(t)}{U_s(t)} = -\beta_F R_C / R_B = -8$$



$$U_{CC} = 12V, U_{BB} = 1.7V, R_B = 100k$$

$$R_C = 4k, \beta_F = 200, \beta_R = 1, U_A = \infty$$

$$U_{BE} = 0.7, U_{CE} = 0.5$$

$$I_{BQ} = 10\mu A, I_{CQ} = 2mA, U_{CEQ} = 4V$$

static load line

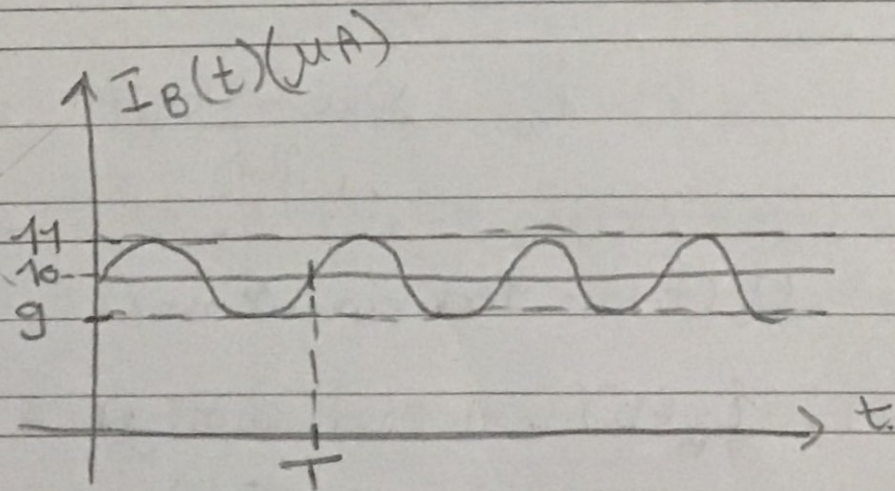
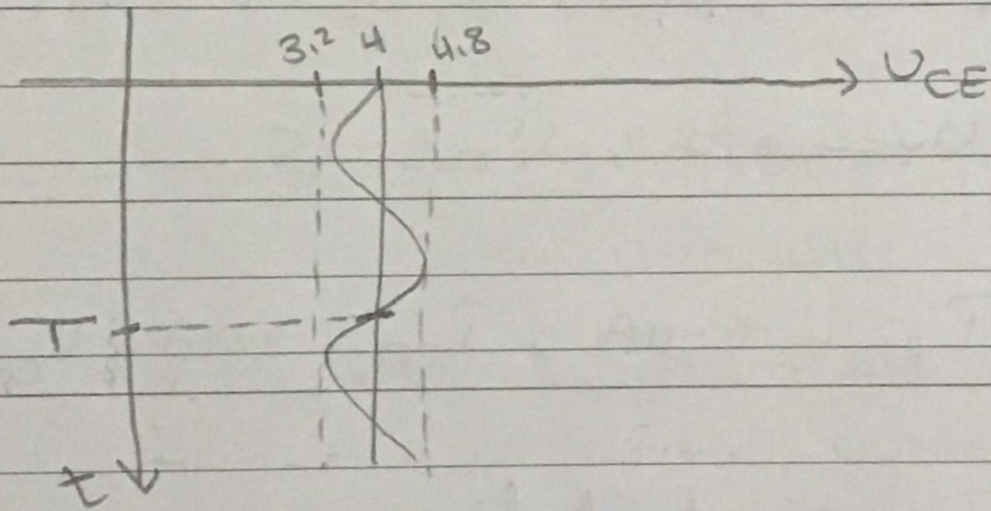
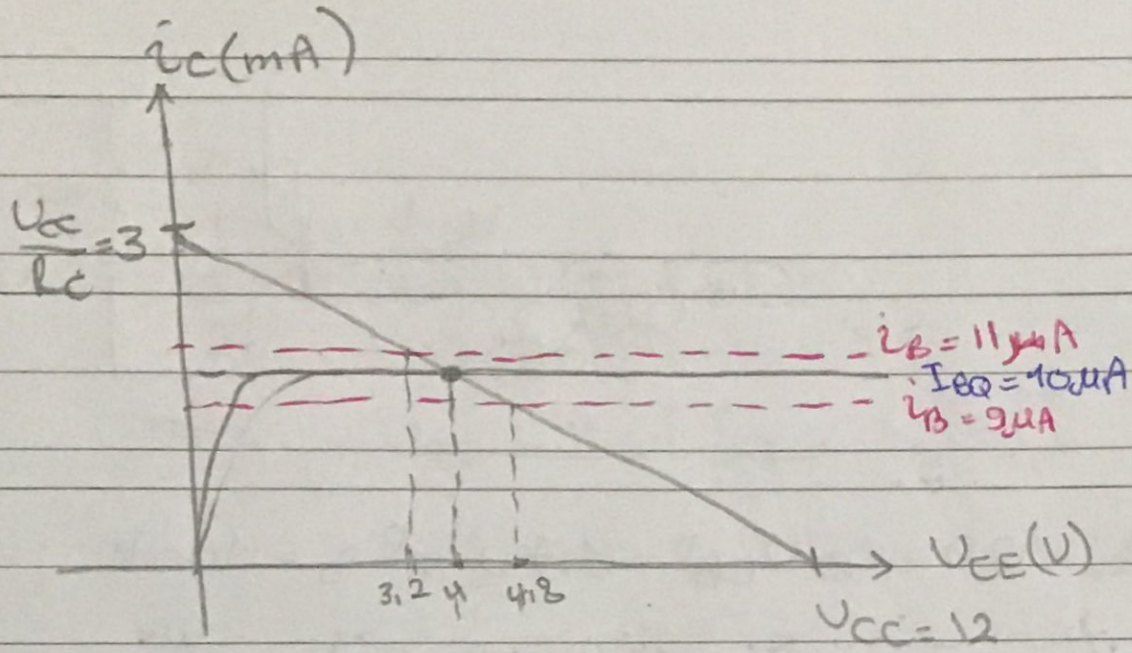
$$i_c = \frac{U_{CC} - U_{CE}}{R_C}$$

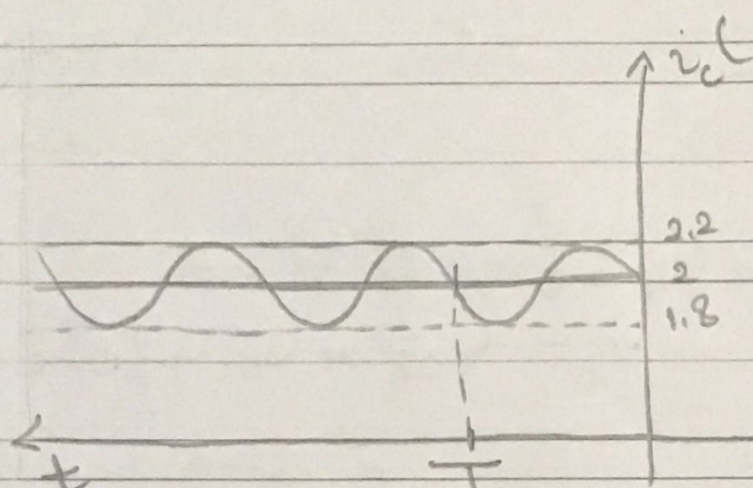
$$U_s(t) = 100 \sin \omega t \text{ mV}$$

$$i_B(t) = 1 \sin \omega t \mu A$$

$$i_c(t) = 200 \sin \omega t \mu A$$

Subject: _____





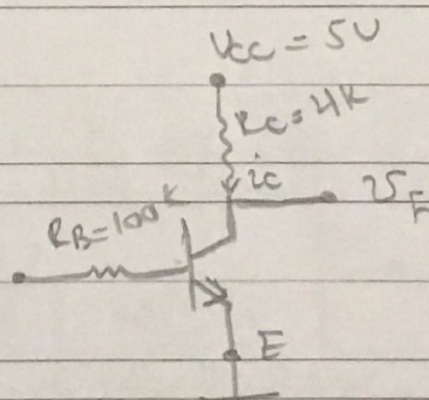
* غالباً تكون نقطة التشغيل في المنتصف لتكون لها

نفس البعد من الزيادة والنقصان

$$V_{BE} = 0.7V$$

$$V_{CE} = 0.5V$$

$$\beta_F = 100$$



if $V_{BB} = 0 \Rightarrow$ npn is cut off

$$\Rightarrow V_F = V_{CC} = 5V$$

if $V_{BB} = V_{CC} = 5V$

Assume npn is forward Active

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5 - 0.7}{100k} = 43\mu A$$

$$I_c = \beta_F \bar{I}_B = 4.3 \text{ mA}$$

$$V_F = V_{CE} = V_{CC} - R_C I_c$$

$$= 5 - 17.2 = -12.2 < V_{CEsat}$$

assumption is wrong
npn is saturated

$$\Rightarrow \bar{I}_B = 43 \mu A$$

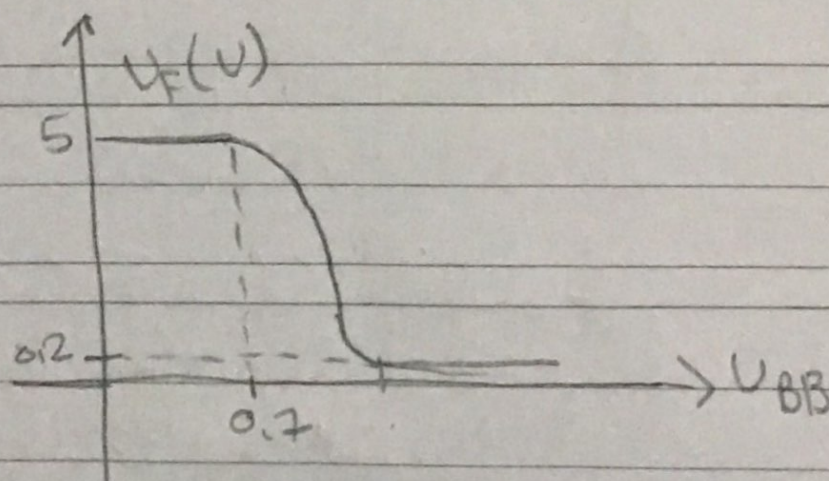
$$V_F = V_{CE} = V_{CEsat} = 0.2 V$$

$$\bar{I}_c = \frac{V_{CC} - V_{CEsat}}{R_C} = \frac{4.8}{4} = 1.2 \text{ mA}$$

inverter

V_{BB}	$V_{CE} \equiv V_F$
0	5
5	0.2

V_{in}	V_o
L	H
H	L



Subject: ch 6 \Rightarrow 3 sections

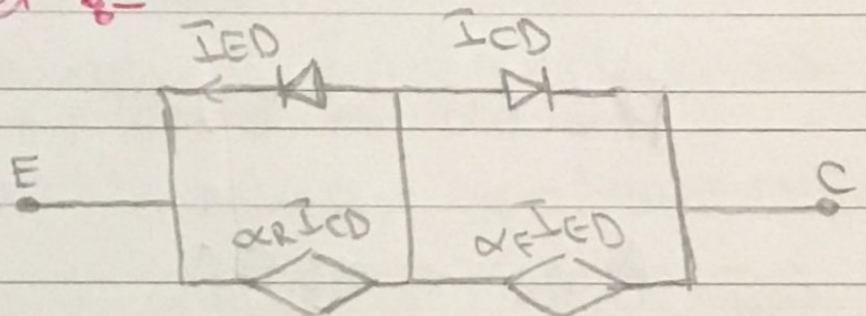
10/6/2017

add 6.28, 6.29, 6.35
6.67

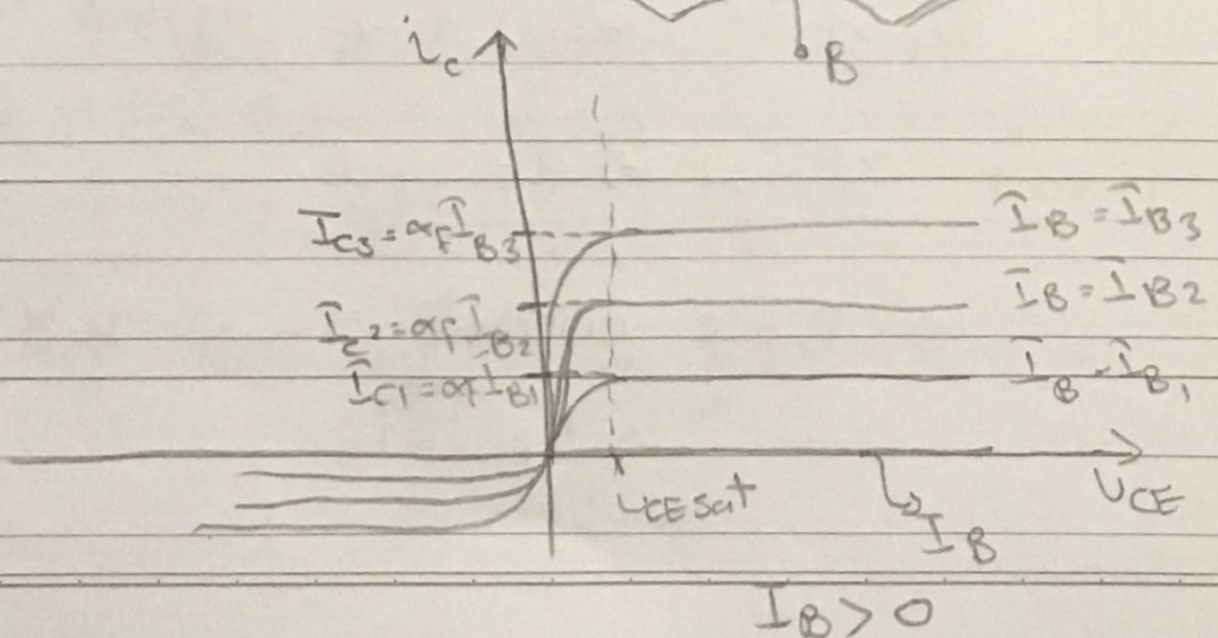
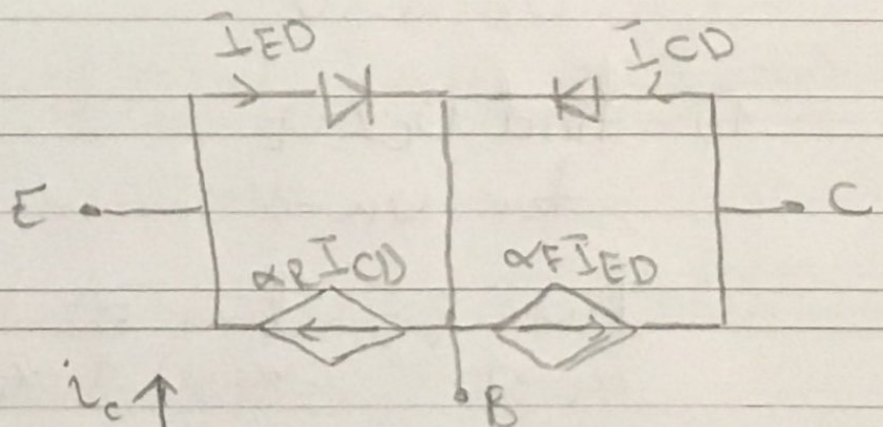
Tutorial

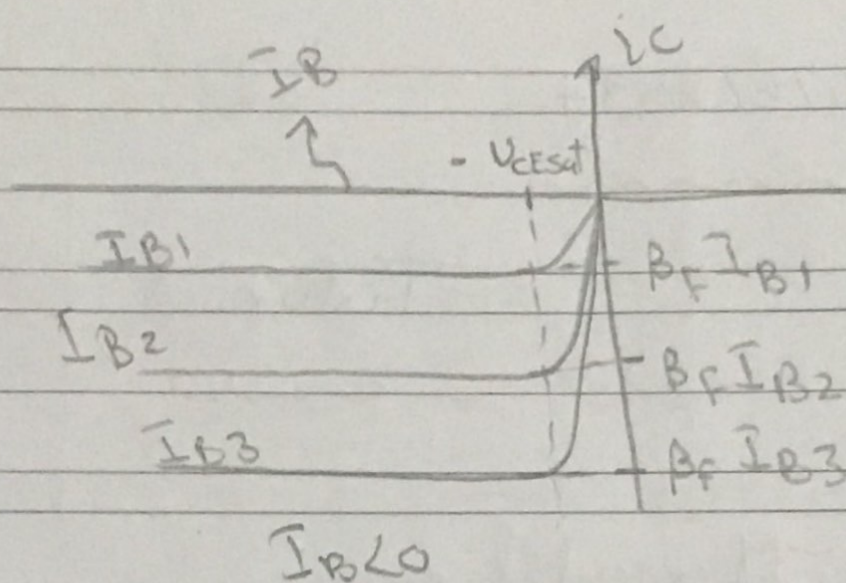
EM model

nnp \Rightarrow



pnP \Rightarrow





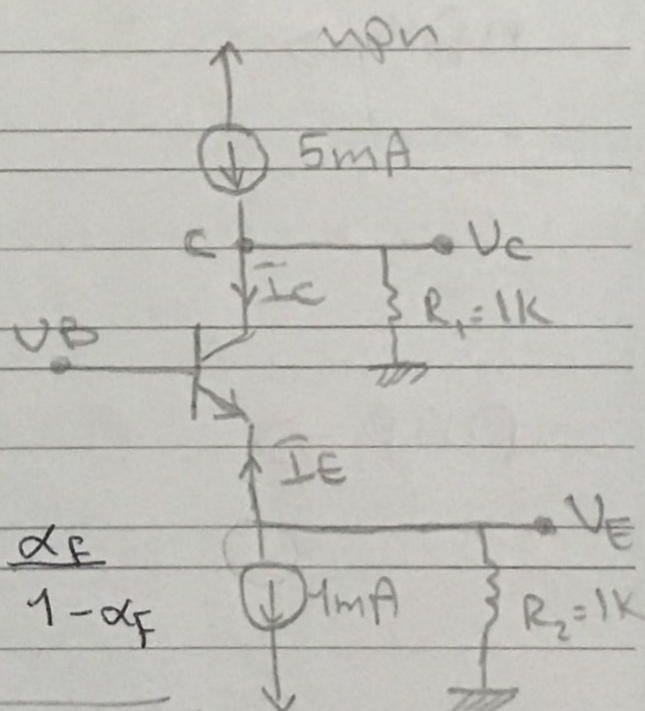
PG. 55 in S&S :-

Assume $\alpha_F \approx 1$

$$V_D = 0.5V$$

1) Find V_C & V_E
for $V_B = 0$

$$\lim_{\alpha_F \rightarrow 1} \beta_F = \lim_{\alpha_F \rightarrow 1} \frac{\alpha_F}{1 - \alpha_F}$$



$\alpha_F \rightarrow 1 \Rightarrow \beta_F \rightarrow \infty$ always

\Rightarrow Base current is neglected ($I_B = 0$)

$$\Rightarrow I_E = -I_C$$

Assume npn is cut off

$$V_E = -1V \Rightarrow V_{BE} = V_B - V_E = 1V > V_{BE}$$

\Rightarrow npn is either F.A or sat

Assume npn is F.A ($V_{BE} = V_{BE} = 0.5V$)

$$V_E = V_B + V_{EB} = V_B - V_{BE} = -0.5V$$

$$V_C = R_1 I_1 = R_1 (5 - I_C) = R_1 (5 + I_E)$$

$$I_E = -(1 + I_2), I_2 = \frac{V_E}{R_2} = \frac{-0.5}{1k\Omega} = -0.5mA$$

$$I_E = -0.5mA$$

assumption

correct

$$V_C = R_1 (5 - 0.5) = 4.5 R_1 = 4.5V$$

$$V_{CE} = V_C - V_E = 5V > V_{CEsat}$$

b// (4) Range of V_B for which npn

is cut off

npn is cut off $\Rightarrow V_{BE} < V_{BE}$

$$V_{BE} = V_B - V_E$$

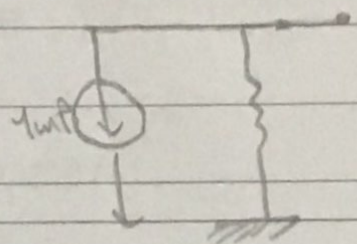
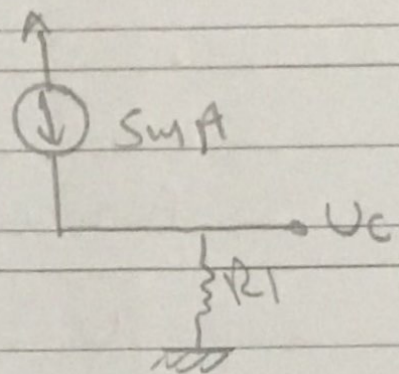
$$V_E = -1V$$

$$U_{BE} = U_{B41}$$

$$V_{BE} < V_{\delta E} \Rightarrow V_{B+1} < 0.5$$

$$\Rightarrow U_B < -0.5$$

$$V_C = 5R_1 = 5V$$



(2) Range of V_B for which npn is saturated Assume $V_{CEsat} = 0$

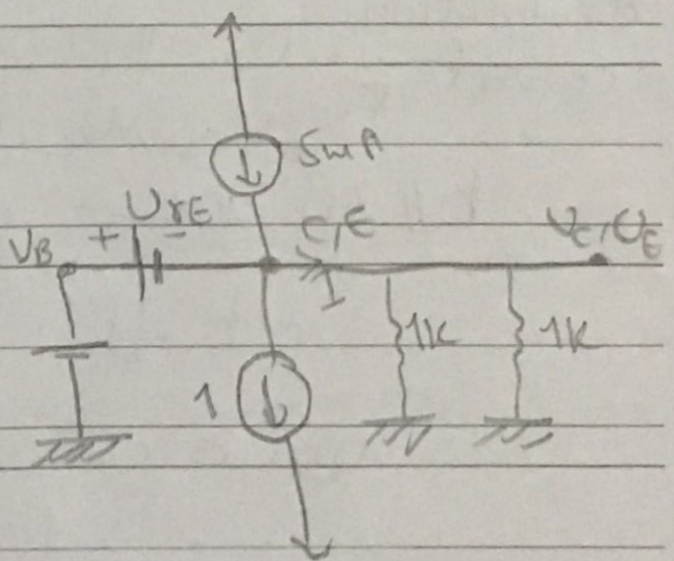
$$I = 5 - 1 = 4 \text{ mA}$$

$$\Rightarrow V_C = V_E = 2V$$

$$U_B = U_{\delta E} + U_E$$

$$= 2.5 \text{ V}$$

npn is saturated for $V_B > 2.5$



* معلومه واحد نخلو اللمقالب

P 6.57

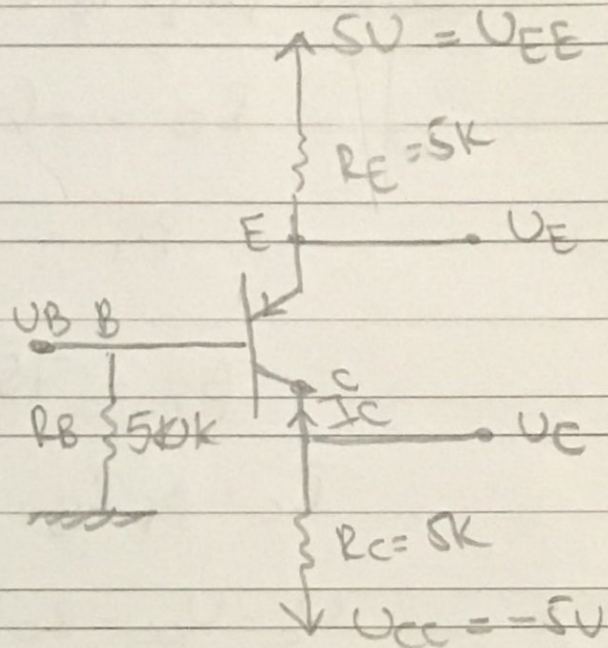
$$|V_{BE}| = 0.7$$

$$V_{BE} = 0.7$$

$$\text{Given: } V_E = 1.2V$$

find I_B, I_C, V_C

$$\beta_F, \alpha_F$$



$$I_E = \frac{V_{EE} - V_E}{R_E} = 0.76 \text{ mA}$$

BJT is npn & $I_E > 0$ \Rightarrow pnp is f.A or sat

$$V_{BE} = -V_{BE} = -0.7V$$

$$V_B = V_{BE} + V_E = 0.5V$$

$$I_B = \frac{0 - V_B}{R_B} = \frac{-0.5}{50k\Omega} = -1\mu A$$

Subject: _____

Assume pnp is F.A

$$I_E = -(1 + \beta_F) I_B$$

$$\beta_F = -\left(\frac{I_E}{I_B} + 1\right) = -\left(\frac{-0.76}{-10} + 1\right)$$

$$\beta_F = 75 \Rightarrow \alpha_F = \frac{75}{76} = 0.987$$

$$I_C = \beta_F I_B = 0.75 \text{ mA}$$

$$\begin{aligned} V_C &= V_{CC} - R_C I_C \\ &= -5 - 5(-0.75) \\ &= -5 + 3.75 = -1.25 \text{ V} \end{aligned}$$

$$\begin{aligned} V_{CE} &= V_C - V_E = -1.25 - 1.2 \\ &= -2.45 \text{ V} \end{aligned}$$

$$V_{CE} < -V_{CE \text{ sat}}$$

\Rightarrow pnp is F.A as assumed